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FEBRUARY 1930

HALE MOUNTAIN SECTION IN NORTHWEST ARKANSAS[1]

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Fayetteville, Arkansas

ABSTRACT

The Hale Mountain section in the southwestern part of Washington County in northwestern Arkansas has long been known and has been visited by many geologists. It is the type locality for the Hale formation and the Morrow group. The easy accessibility of the section and its completeness warrant a detailed description of the formations that comprise the section. These formations range from middle Mississippian to early Pennsylvanian, and include the upper part of the Boone limestone, the Fayetteville shale with the Wedington sandstone member, and the Pitkin limestone, all of Mississippian age; as well as the Hale formation, Bloyd shale with the Brentwood limestone and Kessler limestone members, and the basal part of the Winslow formation, all of early Pennsylvanian age. The accessibility and length of the section, its geographic and geologic location, and a description of the formations, including detailed stratigraphic sections, are considered.

INTRODUCTION

Hale Mountain section has been known for more than a quarter of a century. It has been visited by many geologists, but no attempt hitherto has been made to describe the section in detail. Because of its accessibility, the completeness of the section, the almost continuous outcrop from the foot of Hale Mountain to its top, and the general interest in the earliest sediments of Pennsylvanian age so well exposed, it is thought that a description of the section may be of value.

The Hale formation widely developed in northwest Arkansas is named for Hale Mountain, and the term "Morrow" of the Morrow

[1]Research Paper No. 159, Journal Series, University of Arkansas. Manuscript received by the editor, November 11, 1929.

[2]University of Arkansas.

group is named for a small town located at the north foot of the mountain. The section begins at Morrow and extends to the top of Hale Mountain, a distance of 2.32 miles. The road leading from Morrow southward to the top of the mountain traverses the entire section, making it easily available for study (Fig. 1). The road is not improved, but is passable during all seasons of the year.

GEOGRAPHIC LOCATION OF SECTION

The Hale Mountain section is located in northwest Arkansas in the southwestern part of Washington County, about 4½ miles east of the Oklahoma-Arkansas boundary. Morrow is in the SE. ¼, Sec. 25, T. 14 N., R. 33 W. The section extends southeastward to the southeast corner of Section 36, through the eastern part of Section 6, the northwestern part of Section 8, then westward to the central part of Sec. 7, T. 13 N., R. 32 W. The Winslow quadrangle (surveyed in 1898 by the U. S. Geological Survey) shows the location of Morrow, Hale Mountain, and the general course of the highway connecting the two localities. The location of Morrow is also indicated on the recent state geologic and topographic maps, scale 1:500,000.

LENGTH OF SECTION

The total length of the Hale Mountain section from Morrow postoffice to the top of Hale Mountain is 2.32 miles. The section was measured along the highway leading from Morrow to the top of the mountain. The route followed with locations of stations is shown in Figure 1, and in Table I the distances between the successive stations are given.

ACCESSIBILITY

The Hale Mountain section is readily accessible from several places located on improved highways. From Fayetteville, Arkansas, Highway 45 is followed through Farmington (5.3 miles), Prairie Grove (11.9 miles), Cane Hill (18.9 miles), thence southwest to Clyde (20.4 miles), where the left road is followed southward to Fly Creek, thence westward along the north side of the creek to Morrow (24.3 miles from Fayetteville). Highway 45 is improved to Cane Hill and is passable from there to Morrow except immediately after a heavy rain.

From the Oklahoma-Arkansas line east of Westville, Oklahoma, Arkansas Highway 80 is followed east to Lincoln, Arkansas, from which Morrow may be reached either by going southeast to Cane Hill, then following the road previously described, or by going southward along the

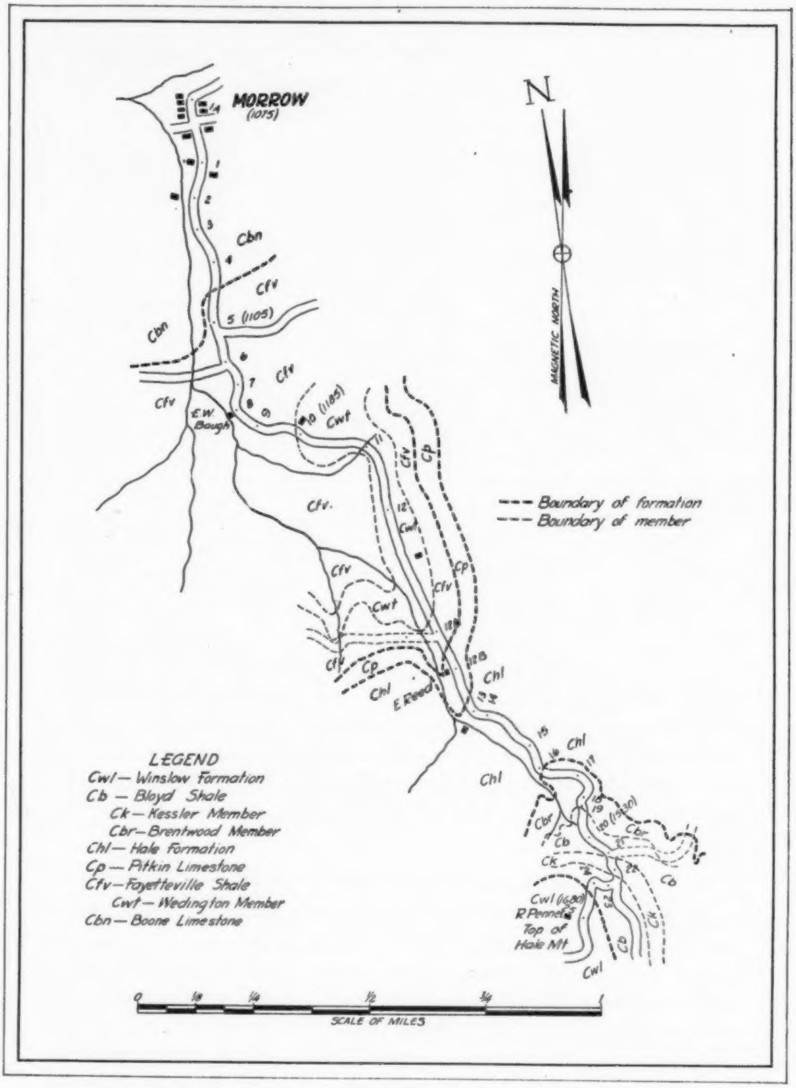

FIG. 1.—Sketch map showing location of Hale Mountain section, stations with their numbers used in making the traverse, and the boundaries of the formations. Numbers in parentheses are altitudes (barometer) in feet.

TABLE I

DISTANCES IN HALE MOUNTAIN SECTION

Stations	*Distance in Feet*
1*A*-1 .... (Morrow)	800
1 -2	400
2 -3	400
3 -4	400
4 -5	700
5 -6	445
6 -7	263
7 -8	300
8 -9	300
9 -10	500
10 -11	790
11 -12	777
12 -13	2,551
13 -14	200
14 -15	553
15 -16	300
16 -17	500
17 -18	266
18 -19	123
19 -20	400
20 -21	300
21 -22	200
22 -23	145
23 -24	200
24 -25 ... (top of Hale Mountain)	456
	12,269 = 2.32 miles

Brush Creek (locally known as Bush Creek) road and entering Morrow from the west. Both routes from Lincoln are unimproved but passable except immediately after heavy rains. From Stillwell, Oklahoma, the road to Morrow leads through Evansville and Dutch Mills, 3½ miles northwest of Morrow. This road also is in good condition and passable except in wet weather.

STRATIGRAPHIC LOCATION OF SECTION

The formations of the Hale Mountain section range in age from the middle Mississippian or Osage (Boone limestone) to the early Pennsylvanian or Pottsville (Winslow formation). The section includes the upper part of the Boone limestone, the Fayetteville shale with the Wedington sandstone member, and the Pitkin limestone, all of Mississippian age; the Hale formation, Bloyd shale with the Brentwood limestone and Kessler limestone members, and the basal part of the Winslow formation, all of early Pennsylvanian age. The stratigraphic succession and age relations are graphically indicated in Figure 2.

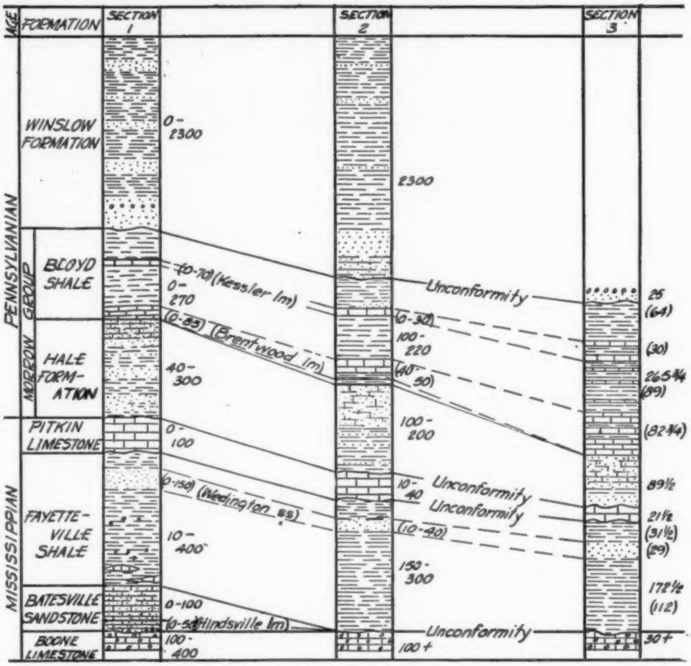

FIG. 2.—Sections above the Boone limestone in northwest Arkansas.
Section 1.—Generalized section compiled from Eureka Springs-Harrison, Fayetteville, Winslow, and Tahlequah folios.
Section 2.—General section of Winslow quadrangle from Winslow folio.
Section 3.—Hale Mountain section.
Scale: 1 inch = approximately 300 feet.

PHYSIOGRAPHY

Hale Mountain is located near the northern limit of the Boston Mountains and near the central part of the prong west of Fayetteville that projects northward from the main mountain mass. The relief of the region, however, is not great, averaging less than 500 feet. The height of the top of Hale Mountain above Morrow is about 600 feet.

The region is drained by small tributaries of Barren Fork, which flows into Illinois River. The immediate vicinity of the section is drained by small tributaries of Fly Creek. These streams carry only a small volume of water except after rains and may be readily forded anywhere

along their courses. Throughout most of their courses they have lowered their channels into the bed rock of the region and reveal excellent stratigraphic sections.

In order to arrive at a conception of the general declivity of the Hale Mountain section, elevations of several of the stations were determined by the use of an aneroid barometer. The elevation of Morrow, 1,075 feet, estimated from the Winslow quadrangle, was taken as the basis for the determinations. The results are given in Table II. Stations showing little difference in elevation from adjacent stations are omitted. As the table indicates, the gradient is steepest between Stations 13 and 25, rising 475 feet in 0.7 mile.

TABLE II

ELEVATIONS OF HALE MOUNTAIN SECTION

Stations	*Feet*
Morrow	Approximately 1,075
5	1,105
6	1,095
10	1,185
13	1,205
16	1,385
17	1,415
18	1,447
19	1,457
20	1,530
21	1,565
22	1,585
23	1,605
24	1,635
25	1,680

DESCRIPTION OF FORMATIONS

The Hale Mountain section consists predominantly of limestone and shale. The Hale formation contains essentially all of the sandstone of the section below the Winslow formation. The limestone is generally massive and fossiliferous, much of it crystalline, generally with conspicuous calcite crystals, weathering to a brown—some of it dark chocolate-brown—mass. The shale is typically argillaceous, weathering to gray soil, and is only locally fossiliferous. The shales of the Hale formation, however, are chiefly sandy and micaceous. The sandstones of the Hale formation are massive and calcareous, locally cross-bedded, and weather to a reddish brown, porous mass. They are very fossiliferous in places.

Few descriptions of stratigraphic sections found in northwest Arkansas have been published. The most recent of the published sections are found in the Eureka Springs-Harrison folio.[1]

The geology of the Hale Mountain region is described in the Winslow folio.[2] This publication also gives a general stratigraphic section of the Winslow region.

In the following paragraphs each formation of the Hale Mountain section is described, beginning with the lowest, the Boone limestone. This sequence is followed because it is the order in which the formations are encountered in going southward from Morrow, the most convenient way of studying the section. The stratigraphic sections tabulated in the text, however, read downward stratigraphically, following the established procedure used in describing sections.

Boone limestone.—The Boone limestone, named by J. C. Branner for Boone County in northern Arkansas, ranges from 100 to 400 feet in thickness in northwestern Arkansas. The formation consists of gray, massively bedded fossiliferous limestone containing considerable gray fossiliferous chert. It is middle Mississippian in age, comprising strata of the Osage and Meramec groups. In northern Arkansas it lies unconformably on the Chattanooga shale or older formations, and is succeeded unconformably by formations of late Mississippian age.

The stream flowing northward through Morrow reveals a good section of the upper part of the Boone limestone, about 30 feet (stratigraphically) of the formation being exposed. Northwest of Morrow, to Dutch Mills and beyond, the stream is floored on the limestone, revealing good sections in its banks. About 1 mile northwest of Dutch Mills the stream is bordered on the south by Boone limestone cliffs 200 feet or more in height. At Morrow the limestone is gray to bluish gray, coarsely crystalline, and fossiliferous. Chert is nearly absent, but just below Morrow along the stream toward the northwest the limestone becomes very cherty. One of the most interesting features of the Boone at Morrow is the presence of large asymmetric ripple marks with their steeper slopes upstream and with a strike of N. 50° E. The ripple marks average 3 feet in length from crest to crest, and 5 to 8 inches in depth, from trough to crest. Fifty-nine ripple marks in continuous sequence were counted in the stream bed west of Station 3.

Fayetteville shale.—The Fayetteville shale was named by F. W. Simonds for the city of Fayetteville in northwest Arkansas. The forma-

[1]"Eureka Springs-Harrison Quadrangle," *Geologic Atlas of the United States Folio 202* (Washington, D. C., 1916).

[2]Winslow Quadrangle," *Geologic Atlas of the United States Folio 154* (Washington, D. C., 1907).

tion ranges from 10 to 400 feet in thickness in northwest Arkansas. It is upper Mississippian (Chester) in age. It consists mainly of black, fissile, highly carbonaceous clay shale with limestone lentils locally developed near the base and a massive light gray to brown sandstone, the Wedington member, developed at or near the top. This member, named for Wedington Mountain, about 15 miles west of Fayetteville, may be absent locally, but it is present in most places with a thickness generally of less than 40 feet. In the Winslow quadrangle it is 40 feet thick south of Prairie Grove, with a thickness somewhat greater south of Lincoln. West of Fayetteville the formation in most places rests unconformably on the Boone, but farther east the Batesville sandstone, with the Hindsville limestone member locally present, occupies the interval between the Boone and the Fayetteville shale.

Locally, the Fayetteville shale is fossiliferous, and its basal portion in places carries a profuse micro-fauna.

In the Hale Mountain section the Fayetteville was found to be 172½ feet thick. The contact of the shale on the Boone is well shown in the creek bed northwest of Station 6. At Station 6 a good section of the black shale is exposed, with continuous outcrop to Station 7. Between Stations 8 and 9, the ditch on the right (south) side of the road reveals a discontinuous sequence of gray clay shale that comprises the middle part of the formation. The section follows.

SECTION OF FAYETTEVILLE SHALE BELOW WEDINGTON SANDSTONE

(Along road between Stations 5 and 10)

	Feet	*Inches*
Wedington sandstone (Station 10)	5+	
Fayetteville shale		
Concealed, probably dark gray clay shale	27	6
Dark gray clay shale with clay concretions	19	6
Concealed, probably shale	25	6
Black, fissile clay shale (Stations 6-7)	30	6
Concealed, probably black shale	7	9
Black, fissile clay shale	1	3
Total	112	0
Boone limestone (west of Station 5)		
Blue to bluish gray, fossiliferous, coarse-grained crystalline limestone with large ripple marks	5+	

The base of the Wedington sandstone is just below Station 10, located in front of the house on the top of the hill. This sandstone forms the flat between Stations 10 and 11. The base of the sandstone, resting

on 3 feet of gray clay shale, is well exposed in the creek bed just southwest of the road at Station 11. The top of the Wedington was found in the field northeast of Station 11 about half-way up the slope toward the outcrop of Pitkin limestone that forms conspicuous ledges near the top of the slope. The thickness of the Wedington here measured 29 feet, the basal part consisting of 5 feet of massive light gray sandstone.

The top of the Wedington is also exposed where the creek crosses the road leading west from the main highway at Station 12*A*. The section continues northward down the creek, but is largely concealed by float. The thickness of the sandstone was found to be 29 feet. The following section indicates the character of the upper part of the sandstone.

SECTION OF UPPER PART OF WEDINGTON SANDSTONE

(In creek bed at Station 12*A*)

	Feet	*Inches*
Upper Fayetteville shale	5+	
Wedington sandstone		
Topmost bed massive, brown, coarse- to medium-grained micaceous sandstone	2	6
Brown, flaggy sandstone	2	6
Gray clay shale with clay concretions and with 5 sandstone layers ½ inch to 2 inches thick interbedded with the shales	3	
Concealed	5+	

About 30 feet of Fayetteville shale intervenes between the Wedington sandstone and the base of the Pitkin limestone. A good section of these shales is exposed in the creek west of the road between Stations 12*A* and 12*B*. The sequence consists chiefly of gray clay shale, as the following section indicates.

SECTION OF FAYETTEVILLE SHALE ABOVE WEDINGTON SANDSTONE

(Along stream west of road between Stations 12*A* and 12*B*)

	Feet	*Inches*
Pitkin limestone (Station 12*B*—home of Earl Reed)		
Massive, fossiliferous gray limestone	3	
Fayetteville shale		
Gray clay shale with small clay concretions	5	6
Concealed	2	
Gray clay shale with small clay concretions		9
Concealed		6
Gray clay shale with small clay concretions	4	3
Concealed		6
Gray clay shale with small clay concretions	9	
Concealed	9	
Total	31	6

Station 12A

	Feet	Inches
Wedington sandstone		
Massive, brown, coarse- to medium-grained sandstone	2	6

Pitkin limestone.—The Pitkin limestone was named for the post-office of Pitkin, 15 miles south of Fayetteville on the Frisco Railroad. The place has since been re-named "Woolsey." In the early reports of the Arkansas Geological Survey the limestone was called "*Archimedes* limestone." The rock is a massively bedded, gray fossiliferous limestone, outcrops of which are readily recognized by the presence of *Archimedes* on weathered surfaces of the strata. Locally it is conglomeratic. The Pitkin limestone attains a maximum thickness of 100 feet in northwest Arkansas, but in most places it is less than 50 feet thick, and in some places absent. In the Winslow quadrangle it ranges from 10 to 40 feet in thickness. It is separated by unconformities from the Fayetteville shale below and the Hale formation above.

In the Hale Mountain section the Pitkin limestone outcrops in conspicuous ledges in the fields above Station 11. A nearly complete sequence is displayed in the stream west of the highway between Stations 12*B* and 13. The thickness of the section was found to be 21½ feet. Another good outcrop with the same thickness forms the slope in the rear of the house of Earl Reed (Station 12*B*). The limestone in these sections exhibits the same general characters as elsewhere, but some of the layers are cherty. The beds are massive, light to dark gray, and fossiliferous with *Archimedes* plentiful. Most of the beds are coarsely crystalline in texture. The following section illustrates in detail the lithologic characters of the formation.

SECTION OF PITKIN LIMESTONE AT THE FOOT OF HALE MOUNTAIN

(Along stream west of road between Stations 12*B* and 13)

Station 13

	Feet	Inches
Pitkin limestone		
Massive, fossiliferous, gray, coarse-grained crinoidal limestone with *Archimedes* and calcite crystals	3	6
Massive, fossiliferous, dark gray crystalline limestone with *Archimedes* and calcite crystals	1	6
Concealed	1	6
Dark gray, fossiliferous crystalline limestone	1	
Dark gray, fossiliferous crystalline limestone with large calcite crystals	1	6
Massive, non-fossiliferous, dark gray medium-grained limestone with calcite crystals	1	

	Feet	Inches
Dense, non-fossiliferous, light gray cherty limestone		6
Coarse-grained, fossiliferous gray limestone	1	
Massive, fossiliferous, gray medium-grained limestone	3	
Massive, fossiliferous, gray cherty limestone	1	
Concealed	3	
Massive, fossiliferous, gray, coarsely crystalline limestone	3	
Total	21	6

Station 12B (House of Earl Reed)

	Feet	Inches
Fayetteville shale		
Gray clay shale	5	6

Hale formation.—In the Tahlequah folio[1] Taff gives the following description of the Hale formation, which he named for Hale Mountain.

> The Hale sandstone in its typical development consists of thick-bedded, massive, calcareous sandstone in the upper part and where it is thickest. In such instances the beds are nearly pure quartz sand of even and moderately fine grain. This member varies in composition locally. In places parts of the member (usually the lower and middle) become so calcareous as to be classed as siliceous limestones. Again it is shaly, consisting of clay and sandy shale with strata of sandstone, especially where the member becomes thin.

This description is applicable to the formation throughout much of northwest Arkansas.

In northwest Arkansas the Hale formation ranges in thickness from 40 to 300 feet. In the Winslow quadrangle it ordinarily ranges from 100 to 200 feet in thickness. It succeeds the Pitkin limestone unconformably, but is conformable with the overlying Bloyd shale. Locally the beds are profusely fossiliferous, some of the sandstone layers carrying plant remains, and the shales in places yielding a microscopic fauna.

In the Hale Mountain section the formation is well exposed on the road between Stations 13 and 16, and along the stream just west of the road. This section was carefully measured, yielding a total thickness of 89½ feet for the Hale formation. The upper two-thirds of the formation consists of massively bedded medium- to fine-grained calcareous sandstone, with a very fossiliferous, massive limestone layer near the middle of the division. Some of the sandstone layers, particularly the one at the top, are also very fossiliferous. The lower third of the section comprises an alternation of thin-bedded sandstones and gray clay and sandy, micaceous shales. The detailed section follows.

[1]*Geologic Atlas of the United States Folio 122* (1905).

SECTION OF HALE FORMATION ON HALE MOUNTAIN

(Along stream west of road, between Stations 13 and 16)

	Feet	*Inches*
Brentwood limestone (Station 16)		
Massive, fossiliferous, dark gray limestone	7	
Hale formation		
Massive, very fossiliferous, yellowish brown, medium- to fine-grained, closely jointed sandstone	3	
Concealed	5	6
Massive, brown, cross-bedded, fine-grained calcareous sandstone with calcite crystals, weathering yellowish brown, pitted and cavernous	23	
Concealed	8	
Massive, very fossiliferous, brownish crystalline limestone with large calcite crystals, weathering reddish and forming a steep bluff at outcrop	4	6
Massive, fossiliferous, brown, calcareous, medium- to fine-grained sandstone, locally conglomeratic and with calcite crystals in some beds, weathering to fluted surface	13	
Gray clay shale with clay-iron concretions	1	
Brownish gray, fine-grained sandstone		6
Gray clay shale with clay-iron concretions	2	6
Sandy, micaceous, brownish gray shale	3	6
Concealed	6	6
Thin-bedded, brown, rippled, coarse- to medium-grained sandstone	2	
Concealed	16	6
Total	89	6
Pitkin limestone (Station 13)		
Massive, fossiliferous coarse-grained limestone with *Archimedes*	3	6

Bloyd shale.—The Hale formation and the Bloyd shale together comprise the Morrow group. The Bloyd shale was named by Purdue for Bloyd Mountain near West Fork, a small town 12 miles south of Fayetteville on the Frisco Railroad. The Morrow group is early Pennsylvanian (pre-Pottsville) in age. In northwest Arkansas the Bloyd shale ranges from almost nothing to 270 feet in thickness, and in the Winslow quadrangle its thickness is nearly everywhere between 100 and 220 feet. The formation consists predominantly of dark, fissile clay shale locally fossiliferous with both megascopic and microscopic forms. Thin coal beds are locally developed near the middle of the formation. A limestone member, the Brentwood limestone, occurs in the lower part of the formation, resting directly on the Hale formation or separated from it by an interval of a few feet occupied by dark clay shale. The Brentwood, named for the station of Brentwood about 18 miles south of Fayetteville on the Frisco Railroad, is a very persistent member of the Bloyd and attains a maximum thickness in northwest Arkansas of nearly 100 feet. In the Winslow quadrangle it is 40-50 feet thick. It is a mas-

sively bedded, bluish to gray, highly fossiliferous limestone, carrying locally a profusion of *Pentremites,* hence the name "Pentremital limestone" in the early reports of the Arkansas Survey.

The Kessler limestone, named by Simonds for Kessler Mountain, southwest of Fayetteville, is a member in the upper part of the Bloyd shale. It is much less persistent than the Brentwood and where present is rarely more than 25 feet thick. With thickness greater than 25 feet much of the member probably consists of gray clay shale. The limestone layers are massive and fossiliferous, brown to gray, and locally conglomeratic. Considerable iron is present so that the beds weather to a dark chocolate color, a diagnostic feature, and contain much limonite.

The Kessler is overlain by a variable thickness—ordinarily less than 75 feet—of gray to nearly black clay shale, comprising the upper part of the Bloyd shale.

The Bloyd shale occupies nearly the entire north slope of Hale Mountain, and is excellently displayed along the highway from Station 16 to the crest of the mountain. The lower part of the section from Station 16 to Station 19 consists of the Brentwood limestone member, 76½ feet thick, heavily bedded, generally fossiliferous, dark to light gray limestone, with two gray clay shale horizons near the top of the member. Eighty-nine feet of gray clay shale containing thin horizons of sandy micaceous shale, and thin ferruginous fossiliferous layers of limestone succeed the Brentwood upward. The overlying Kessler member is 30 feet thick and consists of massive, sandy, fossiliferous and ferruginous limestones alternating with gray to brown clay shale. The upper part of the Bloyd formation consists of fissile gray clay shale with one bed of hard, fine-grained rippled sandstone and two beds of sandy ferruginous limestone weathering to a chocolate-brown. This division of the Bloyd is 64 feet thick. The detailed characters of the Bloyd shale, measured along the highway, are given in the following section.

SECTION OF BLOYD SHALE ON HALE MOUNTAIN

(Along road between Stations 16 and 25)

Station 25 (Top of Hale Mountain)

	Feet	*Inches*
Winslow formation		
Conglomerate with small white quartz pebbles in a matrix of coarse-grained, dark brown sandstone with limonite concretions......		9
Coarse-grained, friable, yellowish brown, iron-stained, cross-bedded sandstone..........	2	
Coarse-grained, friable, yellowish brown, iron-stained, cross-bedded sandstone..........	23	
Total..........	25	9

	Feet	Inches
Bloyd shale above Kessler limestone		
Concealed	1	
Thin-bedded, fissile, gray clay shale	1	6
Concealed, probably shale	12	6
Thin-bedded, fissile, gray clay shale	5	
Concealed, probably shale	2	
Station 24		
Concealed, probably shale	3	6
Hard, fine-grained, light yellowish gray rippled sandstone	1	
Thin-bedded, fissile, gray clay shale	8	
Sandy, limonitic, concretionary leached limestone, weathering yellow to chocolate-brown		6
Thin-bedded, fissile, gray clay shale	5	
Sandy, cross-bedded, fossiliferous, brownish, medium-grained limestone with calcite stringers and crystals, weathering to chocolate-brown, with fluted surface		6
Thin-bedded, fissile, gray clay shale	11	
Station 23		
Thin-bedded, fissile, gray clay shale	12	6
Total	64	0
Kessler limestone member of Bloyd shale		
Massive, sandy, cross-bedded, fossiliferous, brownish, medium-grained limestone with calcite stringers and crystals, weathering to chocolate-brown, with fluted surface	4	
Fissile, gray clay shale with clay-iron concretions	3	
Station 22		
Massive, locally sandy and micaceous, fossiliferous, dark gray to brownish, medium-grained limestone with calcite crystals, weathering shaly and to a chocolate-brown	6	
Gray to brown clay shale with clay-iron concretions	11	
Fossiliferous, sandy, ferruginous limestone weathering brown, soft, and porous		6
Gray to brown clay shale with clay-iron concretions	1	
Station 21		
Massive and thin-bedded, very fossiliferous, dark gray, fine to coarse-grained conglomeratic limestone with limonite concretions, weathering shaly	4	6
Total	30	0
Bloyd shale below Kessler limestone		
Gray to brown clay shale with clay-iron concretions	20	6
Gray, sandy, micaceous platy shale	2	6
Gray to brown clay shale with clay-iron concretions	5	6
Station 20		
Gray to brown clay shale with clay-iron concretions	33	
Fossiliferous, sandy, ferruginous limestone weathering brown, soft, and porous		6
Gray to brown clay shale with clay-iron concretions	12	
Massive, coarse-grained, very fossiliferous, medium gray crystalline limestone with calcite crystals	1	6

	Feet	Inches
Ferruginous, sandy clay limestone weathering brown, very fossiliferous, with trilobites		6
Gray to brown clay shale with clay-iron concretions	13	
Total	89	0

Brentwood limestone member of Bloyd shale

	Feet	Inches
Massive, fossiliferous, brownish gray conglomeratic limestone weathering brown and limonitic		6
Massive, fossiliferous, dark gray, coarse-grained crystalline limestone with calcite crystals	3	
Concealed	1	
Massive, fossiliferous, medium gray, medium-grained limestone with calcite crystals and stringers	1	
Station 19		
Massive, fossiliferous, dark gray, fine-grained limestone	1	
Massive, fossiliferous, dark gray, fine- to medium-grained limestone with calcite crystals	1	
Thin-bedded, bluish gray, fissile clay shale	3	6
Massive, very fossiliferous, coarsely crystalline gray limestone weathering brownish	4	
Station 18		
Thin-bedded, bluish gray, fissile clay shale	11	
Massive, fossiliferous, dark gray, bituminous fine-grained limestone		6
Massive, fossiliferous, dark gray, fine-grained limestone with calcite crystals and stringers	2	
Concealed	1	
Massive, fossiliferous, brownish, very coarse-grained crystalline limestone with large calcite crystals	1	
Concealed, probably limestone	1	6
Massive, fossiliferous, brownish, very coarse-grained crystalline limestone with large calcite crystals	1	6
Concealed		6
Massive, fossiliferous, medium-grained brownish limestone with calcite crystals	1	6
Massive, fossiliferous, dark gray, medium- to coarse-grained limestone with calcite crystals	4	6
Concealed, probably shale	3	6
Station 17		
Massive, fossiliferous, brownish gray, coarse-grained crystalline limestone with calcite crystals	1	6
Massive, fossiliferous, light gray crystalline limestone	1	
Massive, fossiliferous, medium gray, very coarse-grained crystalline limestone with calcite crystals	3	6
Massive, fossiliferous, sandy, brown fine-grained limestone	1	6
Massive, fossiliferous, medium gray, coarse-grained crystalline limestone with calcite crystals	2	6
Massive, fossiliferous, medium gray, coarse-grained crystalline limestone with calcite crystals		6
Concealed, probably limestone		6
Massive, fossiliferous, gray to pink, coarse-grained crystalline limestone with calcite crystals	2	6
Concealed		6
Massive, fossiliferous, gray to pink, coarse-grained crystalline limestone with calcite crystals	1	
Massive, very fossiliferous, brownish, coarse-grained crystalline limestone with calcite crystals	2	6

	Feet	*Inches*
Massive, fossiliferous, dark gray, fine-grained crystalline limestone with calcite crystals		6
Massive, fossiliferous, pink, very coarse-grained crystalline limestone with calcite crystals	1	
Massive, fossiliferous, dark gray fine-grained limestone with calcite crystals		6
Massive, fossiliferous, brownish crystalline limestone with large calcite crystals		6
Massive, fossiliferous, dark, bituminous fine-grained limestone		6
Massive, very fossiliferous, brownish crystalline limestone with calcite crystals	1	6
Massive, fossiliferous, light gray coarse-grained limestone with calcite crystals	1	6
Massive, fossiliferous, pink coarse-grained limestone with calcite crystals		6
Massive, fossiliferous, light gray coarse-grained limestone with calcite crystals	2	
Massive, fossiliferous, dark gray, medium- to coarse-grained limestone with calcite crystals	7	
Total	76	6

Station 16

	Feet	*Inches*
Hale formation		
Massive, fossiliferous, yellowish brown sandstone	3	0

A very good section of the Brentwood is revealed in the bottom of the ravine west of the highway between Stations 16 and 20. The ravine heads on the west side of the highway just south of Station 19. The total thickness of the Brentwood was found to be 82¾ feet. The section follows.

SECTION OF BRENTWOOD LIMESTONE ON HALE MOUNTAIN

(Section begins on road 215 feet south of Station 19 and continues northwestward down creek toward Station 16)

	Feet	*Inches*
Bloyd shale		
Gray to brown clay shale with clay-iron concretions	12	6
Concealed, probably shale	5	
Gray to brown clay shale with clay-iron concretions	10	
Total	27	6
Brentwood limestone member of Bloyd shale		
Massive, very fossiliferous, dark gray conglomeratic limestone weathering chocolate-brown		6
Massive, fossiliferous, fine-grained, gray oölitic limestone	1	
Massive, fossiliferous weathered limestone	1	
Massive, fossiliferous, medium gray coarse-grained limestone with calcite crystals	1	6
Massive, dark gray, coarse-grained crystalline limestone with calcite crystals	1	6
Concealed	2	6
Gray clay shale	3	6

	Feet	Inches
Massive, fossiliferous, dark gray coarse-grained limestone with calcite crystals	1	
Concealed	2	6
Massive, fossiliferous, dark gray coarse-grained limestone	1	6
Concealed	6	6
Dark gray clay shale	3	
Shaly, dark, bituminous fine-grained limestone		3
Massive, fossiliferous, dark gray fine-grained limestone	1	6
Weathered clay shale	3	
Massive, very fossiliferous, light gray, coarse-grained crystalline limestone with calcite crystals	1	6
Massive, very fossiliferous, brownish coarse-grained limestone with calcite crystals and stringers, weathering shaly	5	6
Concealed	3	
Gray clay shale	2	
Concealed	1	
Massive, very fossiliferous, dark gray medium-grained limestone with calcite crystals, weathering shaly	2	
Massive, fossiliferous, dark gray coarse-grained limestone	4	
Massive, fossiliferous, dark gray, fine- to medium-grained limestone	1	
Massive, very fossiliferous, dark gray, coarse-grained crystalline limestone with calcite crystals		6
Massive, fossiliferous, brownish crystalline limestone with calcite crystals, weathering shaly	4	6
Concealed, probably limestone	8	
Massive, fossiliferous, chocolate-colored, medium-grained crystalline limestone with calcite crystals		6
Thin-bedded, brownish, fossiliferous crystalline limestone	1	
Concealed, probably limestone	4	
Massive, fossiliferous, light gray, medium- to coarse-grained crystalline limestone with calcite crystals, weathering brownish	1	6
Massive, fossiliferous, medium gray fine-grained limestone	1	6
Massive, very fossiliferous, pinkish gray, coarsely crystalline limestone with calcite crystals	4	6
Massive, fossiliferous, medium gray fine-grained limestone with calcite crystals		6
Massive, fossiliferous, dark gray medium-grained limestone with calcite crystals	5	6
Total	82	9
Hale formation		
Massive, very fossiliferous yellowish brown sandstone	2+	

Winslow formation.—The Winslow formation (basal Atoka) named for the town of Winslow in the Boston Mountains 22 miles south of Fayetteville, is Pottsville in age, and closely resembles lithologically the Pottsville of the Appalachian region. It is very thick in the main mass of the Boston Mountains, but in the northern part of those mountains and in the outliers north of the mountains the formation is found only in the upper parts of the summits. The Winslow consists of coarse sandstone and conglomerate alternating with shale, the sequence unconformably succeeding the Bloyd shale. Massive, gray to brown cross-bedded sandstone normally overlies the shale of the Bloyd.

On Hale Mountain only a few feet of the basal Winslow is present, the section on the highway north of Station 25 measuring 25 feet. The sandstone here is coarse-grained, friable, yellowish brown, iron-stained, and cross-bedded. Two feet above Station 25, on the right (west) side of the road, a conglomeratic layer 9 inches thick was found. This layer consists of coarse-grained, dark brown sandstone with limonite concretions and small white quartz pebbles. This layer is very persistent in northwest Arkansas. In fact, the persistence and the location of the bed just above the base of the Winslow formation is of considerable diagnostic significance in mapping the base of that formation. The stratigraphic succession is given in the preceding section describing the Bloyd shale.

DISCUSSION

Fanny Carter Edson, Tulsa, Oklahoma: The authors have most ably described a very interesting stratigraphic section, one which is of the greatest importance to Mid-Continent stratigraphers. The outcrops on Hale Mountain include the equivalents of the Atoka beds, "Gilcrease sand," "Wapanucka lime," "Cromwell sand," "Fayetteville," "Mayes," and "Caney" shales of the Greater Seminole area—beds familiar to all Mid-Continent petroleum geologists. The careful directions given for reaching these easily accessible outcrops, the very excellent descriptions of the various formations, and the measured sections all combine to make this paper a real contribution to Mid-Continent stratigraphy.

CAUSATIVE AGENTS OF SULPHATE REDUCTION IN OIL-WELL WATERS[1]

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ABSTRACT

That inanimate organic matter reduces sulphates in oil-well waters seems to be a tradition, rather than a confirmed fact. The writer reviews the problem in the light of early and recent investigations. Biological research is suggested. A bibliography is given in the footnotes.

INTRODUCTORY STATEMENT

It is not the intent here to discuss the many geological conditions which are associated with sulphur, hydrogen sulphide, and other sulphides. The endeavor here is to state the problem relative to sulphate reduction in water, particularly in oil-well waters.

Many observers of the past have directed our attention to the fact that waters occurring with oil or adjacent to oil-bearing horizons contain, in general, only a small amount of sulphate, and many of these waters are found devoid of sulphates. There are, of course, exceptions to this rule, one of them being the subsurface waters of parts of West Texas.

The concensus of opinion is that sulphates in waters of marine or terrane origin have been chemically reduced. This seems to be a logical deduction. There is small doubt, however, that sulphate concentrations in some places have been diminished or depleted by the intermingling of another water, which is itself free of sulphates, but which carries a base, the sulphate of which is insoluble or only sparingly soluble. The chemical precipitation of sulphates is outside the scope of this paper.

The interpretations of the cause of sulphate reduction have brought about two schools of thought: (1) that sulphates have been, or are now being, reduced in nature's deep-seated geochemical laboratory, by inanimate organic matter, such as petroleum, petroleum hydrocarbons, and carbonaceous matter in general, and (2) that the sulphates have

[1]Read before the Tulsa Geological Society, November 4, 1929. Manuscript received by the editor, November 25, 1929.

[2]Tulsa Laboratories, 102½ East Third Street. Introduced by Robert H. Dott.

been, and at the present time are being, reduced to sulphides by animate matter (anaerobic micro-organisms).

The writer's interest in this subject of causative agents has been greatly stimulated by discussion with his friends of the geological profession, and it is his endeavor in this paper to set forth briefly the views of recent writers, pointing out the interpretations that have not been proved to be fact, and those which at present seem to be fact.

EARLY AND RECENT INVESTIGATIONS

The chapter on the ocean in Clarke's[1] "Data of Geochemistry" is sufficient to introduce the subject matter. He refers to the reduction of sulphates in the muds and the bottom waters of the inland seas, by decomposing organic matter, to sulphides, which, by reaction with carbonic acid, yield hydrogen sulphide. He states further, referring to the early work of Androussof,[2] that bacteria assist in the process, which is particularly manifested in the bottom waters of the Black Sea.

Rogers,[3] in his study of the oil-well waters in San Joaquin Valley, California, points out that the surface waters and the shallow ground waters contain more sulphates, and that with the increase of depth, the sulphates diminish and the carbonates increase. His interpretation is that the sulphates in waters associated with oil, or close to oil measures, are reduced to sulphides by hydrocarbon constituents of the oil, the reaction producing a chemical equivalent of carbon dioxide.

In a later contribution,[4] published in 1919, Rogers shows the same relations of sulphate, sulphide, and carbonate waters with respect to the oil measures in the Sunset-Midway oil field of California. He again gives the same interpretation of the cause of the sulphate reduction, admitting, however, that the reasoning was purely speculative, inasmuch as it is not known that inanimate organic matter, at reasonably low temperatures, can be oxidized by the sulphate radicle.

Rogers took cognizance of the early work of Lothar Meyer[5] and others, who disclosed the fact that bottom waters of some of the inland

[1] F. W. Clarke, "Data of Geochemistry," *U. S. Geol. Survey Bull. 770* (1924), p. 150.

[2] N. Androussof, *Guide des Excursions du VII Cong. Internat.*, No. 29.

[3] G. Sherburne Rogers, "Chemical Relations of the Oil-Field Waters in San Joaquin Valley, California," *U. S. Geol. Survey Bull. 653* (1917), p. 6.

[4] G. Sherburne Rogers, "The Sunset-Midway Oil Field, California," *U. S. Geol. Survey Prof. Paper 117*, Pt. 2 (1919), pp. 26-29.

[5] Lothar Meyer, "Chemische Untersuchung der Thermen zu Landeck in der Grafschaft," *Jour. prakt. Chemie*, Band 91 (1864), pp. 5-6.

seas contained anaerobic micro-organisms, which had the property of reducing the sulphate radicle to sulphide. However, Rogers did not consider that this type of reduction had any bearing on the sulphate reduction of oil-well waters, for at that date it was considered very doubtful (and it is so considered now by many) that these micro-organisms could exist in these sea muds after they were covered with thousands of feet of sediments. Rogers accordingly concluded that this life could not continue to exist under these conditions.

Mills and Wells,[1] in their study of the evaporation and concentration of oil-well waters, refer to the contribution of Murray and Irvine,[2] who show that the sea water associated with the blue mud deposits at the bottom contains about half the sulphates of normal sea water. This reduction was attributed to the decomposition of organic matter. Murray and Irvine found that the proportion of the carbonates in the mud water increased, and that an unstable form of iron sulphide was deposited in the mud. Mills further states, referring to the work of Lothar Meyer,

> It has been proved that the reduction of sulphates and the contemporary formation of carbonate and sulphide are due not merely to the presence of decomposing organic matter, but to the action of micro-organisms.

Mills agreed with Rogers, relative to the causative agents of sulphate reduction in oil-well waters.

The literature discloses many interesting facts relative to this sulphate reduction in oil-well waters and subsurface horizons. Each day we gratefully accept man's contributions pertaining to his new experiences. However, interpretations as to cause are not necessarily facts, and it is that phase of the subject in which we are interested at this time. From a casual view, the interpretation of Rogers and others seems plausible, and investigators generally agree that sulphates in subsurface waters, associated with, or adjacent to, oil measures, have been reduced to sulphides, which in turn would be converted, in the presence of water and carbon dioxide, to carbonates, the sulphide radicle being set free as hydrogen sulphide. If we accept this concept as truth, and the reducing agent as inanimate matter of a carbonaceous or hydrocarbon nature, the conclusion inevitably follows that the hydrocarbon constituents

[1] R. Van A. Mills and Roger C. Wells, "The Evaporation and Concentration of Waters Associated with Petroleum and Natural Gas," *U. S. Geol. Survey Bull. 693* (1919), p. 70.

[2] John Murray and Robert Irvine, "On the Chemical Changes Which Take Place in the Composition of the Sea Water Associated with Blue Muds on the Floor of the Ocean," *Trans. Roy. Soc. Edinburgh*, Vol. 37 (1895), pp. 481-508.

have been oxidized by the combined oxygen of the sulphate radicle, free oxygen being absent from the system. This, as pointed out by many, is not in accord with the chemical investigations of the laboratory. The conditions, as we know them, which are necessary to bring about the oxidation of carbonaceous matter by the combined oxygen of the sulphate radicle, are considered later in this paper.

Renick,[1] from his study of artesian waters in Montana, concludes that methane has the power of reducing the sulphate radicle, for eight of the ten artesian waters from the Lance formation were found to carry 37-66 cubic centimeters of methane per liter, and only a trace of sulphates, whereas two of the waters contained 979 and 1,594 parts per million of sulphates, and no methane. The wells investigated ranged from 150 to 900 feet in depth and produced soft water from the sandstones of the Lance, which also carries some coal beds. Renick is of the opinion that the source of the methane is the Lance coal beds. It is conjectural whether this methane-sulphate relation is indicative of sulphate reduction, or whether it is merely an interesting coincidence.

Estabrook,[2] in his contribution on the oil-well waters of a Wyoming oil field, points out that the waters associated with the oil were, in the main, very low in sulphates. The exceptions seemed to be explained by the admixing and circulation of surface water through the outcrops to the wells. He also reports that the oil associated with the edge water was considerably lower in Baumé gravity than the oil from the same formation in the center of the field. Estabrook attributes this alteration of gravity to a chemical reaction between the sulphates and the oil.

Parks[3] writes of the oil-well waters in the Poison Spider field, Wyoming, and his interpretation relative to the sulphate reduction in the waters associated with oil is the same as that of the others mentioned.

We now leave this school of thought, which suggests that the inanimate organic matter, at reasonably low temperatures, is oxidized by the sulphate radicle, and peruse briefly the evidence pointing to a biological reduction of the sulphates in sedimentary rocks and oil-well waters, the inanimate organic matter serving as a source of energy for anaerobic micro-organisms.

[1]B. Coleman Renick, "Some Geochemical Relations of Ground Water and Associated Natural Gas in the Lance Formation, Montana," *Jour. Geol.*, Vol. 32 (1924), pp. 668-85.

[2]Edward L. Estabrook, "Analyses of Wyoming Oil-Field Waters," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 9 (1925), p. 235.

[3]E. M. Parks, "Water Analysis in Oil Production," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 9 (1925), p. 927.

Bastin[1] studied the action of bacteria in geochemical phenomena, and found that many Illinois oil-well waters from the Pennsylvanian, Mississippian, and Ordovician horizons contained anaerobic bacteria which were successfully cultured in the laboratory. These waters ranged in concentration from 6.2 to 63.9 grams of solids per liter. Twenty-eight sulphate-reducing cultures were obtained from thirty of these oil-well waters. The strains isolated proved to be strict anaerobes which had the power of reducing sulphates to sulphides. He states that this type of bacteria was also found in some of the oil-well waters of the Sunset-Midway field, California.

Bastin reported that the three strains studied seemed to be morphologically and culturally identical with the strains which have been studied in Europe by Beyerinck, van Delden, Elion, and others. These European workers isolated their strains from various places, such as the sea, sea muds, and water-well core samples.

Beyerinck,[2] in 1895, contributed a study on a strict anaerobe which was isolated from ditch mud. This anaerobe (*Microspira desulfuricans*) had the property of reducing sulphates. The optimum temperature for the organism was found to lie between 25° and 30° C.

Van Delden[3] isolated a sulphate-reducing bacterium from the shallows along the Dutch coast, which he named *Microspira aestuarii*. This organism is morphologically the same as Beyerinck's *Microspira desulfuricans*, but differs culturally in that a certain amount of sodium chloride is necessary for its growth.

Issatchenko,[4] in 1924, confirmed the early work of van Delden in his study of the micro-organisms of the Black Sea.

L. Elion[5] recently isolated a third species of these anaerobic sulphate-reducing bacteria which he called *Vibrio thermodesulfuricans*. The morphology of this species is the same as that of the other two mentioned; however, it differs principally in demanding a rather high tem-

[1] Edson S. Bastin, "The Problem of the Natural Reduction of Sulphates," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), p. 1270.

[2] W. M. Beyerinck, "Über Spirillum desulfuricans als Ursache von Sulfat-Reduction," *Centralblatt für Bakteriologie* (Ab. 2), Vol. 1 (1895), pp. 1-9 and 104-14.

[3] A. van Delden, "Breitrag zur Kenntnis der Sulfatreduktion durch Bakterien," *Centralblatt für Bakteriologie* (Ab. 2), Vol. 11 (1903-04), pp. 81-94 and 113-19.

[4] Issatchenko, "Sur la fermentation sulfhydrique dans la mer noire," *Compt. Rend.* (Paris), Vol. 178 (1924), p. 2204.

[5] L. Elion, "A Thermophilic Sulphate-Reducing Bacterium," *Centralblatt für Bakteriologie* (Ab. 2), Vol. 63 (1924-25), pp. 58-67; also, L. Elion, "Formation of Hydrogen Sulfide by the Natural Reduction of Sulfates," *Jour. Ind. Eng. Chem.*, Vol. 19 (1927), p. 1368.

perature for its optimum growth. Elion reported the optimum temperature to be approximately 55° C.

Gahl and Anderson,[1] in 1928, contributed a further study on sulphate-reducing bacteria which were found in California oil-well waters. The authors isolated anaerobic sulphate-reducing bacteria from the waters of seventeen wells, the total number sampled in the Sunset-Midway field being forty. None of these strains was isolated from surface waters; the shallowest well containing these anaerobes was 760 feet; the deepest well giving a positive culture was 3,090 feet. They conclude that the anaerobes isolated were similar to, if not identical with, the strains described by Beyerinck, van Delden, and Elion. The temperatures of the waters sampled were found to range from 44° to 47° C.

ANALYSIS OF VIEWPOINTS

In order to summarize the evidence of cause, the concept that the sulphate radicle oxidizes the inanimate organic matter, such as carbonaceous residues and petroleum, is again referred to. In industry and in the laboratory this reaction does occur in the absence of air, at high temperatures (700°-1,000° C.), whereas the temperatures of the earth sediments are, and probably have always been, reasonably low with a few exceptions, such as diastrophism affecting anthracite formation, relatively small lateral areas affected by vulcanism, and possibly a reasonably high temperature on the flanks of anticlines where the greatest flexure and movement have occurred during mountain folding. In general, the writer believes it is reasonable to assume that the lateral areas affected by these movements and forces are small, compared with the great areas of the sediments as a whole.

The following conventional equations illustrate sulphate reduction by inanimate organic matter, as it occurs in the plant and the laboratory.

$$(1)\quad R.SO_4 + 4L + 700^\circ \text{ to } 1{,}000^\circ\ C. = RS + 4CO$$

$$(2)\quad R.SO_4 + 2C + 700^\circ \text{ to } 1{,}000^\circ\ C. = RS + 2CO_2$$

$$(3)\quad RS + HOH + CO_2 + \text{room temperature} = R.CO_3 + H_2S$$

Rogers suggests that possibly we may find organic compounds in petroleum, other than the hydrocarbons with which we are familiar, acting as reducing agents. Work of the future may prove that this is a fact; however, at the present time the writer is not aware of any evi-

[1] Rudolf Gahl and Belle Anderson, "Sulfate-Reducing Bacteria in California Oil-Well Waters," *Centralblatt für Bakteriologie* (Ab. 2), Vol. 73 (1928), p. 331.

dence which indicates that inanimate organic matter is oxidized by the sulphate radicle at the reasonably low temperatures of the earth's sedimentary rocks.

Renick's disclosure of methane associated with artesian waters which were devoid of sulphates is interesting, although, in order for one to accept his interpretation, it is necessary to overlook the fact that the ignition point of methane in the presence of air is approximately 600° C.

Bastin made tests of various sulphates in contact with oils through a period of a year, with negative results from the standpoint of sulphate reduction.

On the contrary, certain anaerobic flora which have been mentioned exist at the present time in inland seas which are not greatly disturbed by current action. The geological evidence pertaining to the habitats of fauna and flora suggests that these same or similar strains could have existed from early sedimentary time to the present. And now through the work of Bastin, Gahl, and Anderson, we are provided with the information that anaerobes at the present time occur in some of the deep subsurface waters of the oil fields. The writer does not care to go so far, at this time, as to infer that these organisms were entrapped with the sediments and have been there ever since. It is necessary to keep in mind that, at the time Sherburne Rogers contributed his exhaustive study of the geochemical relations of oil, gas, and water, this last bit of information was not available. Mills concurs with Rogers in concluding that these sulphate-reducing organisms could not continue to exist after being covered with thousands of feet of sediments. However, it is natural to seek some explanation for the present occurrence of these anaerobes, with full knowledge that there are many problems which now seem insusceptible of proof.

The question as to how these bacteria gained access to these old subsurface horizons and how long they have been there is somewhat provocative. If the imagination is unnecessarily strained in assuming that these bacteria have been present since the time of deposition, then the outcrop as a source of entry may be the more plausible explanation. It is assumed, for the purpose of illustration, that these anaerobes are found in the "Siliceous lime" (Ordovician) of Kansas, and in the "Siliceous lime" of parts of Oklahoma, and that the sources of entry were the outcrops in the Ozark and the Arbuckle mountains; also the writer feels that the time interval—from the Permian to the present—is sufficient for extensive lateral dissemination of micro-organisms, as the rate of movement should be greater than that provided by chemical diffusion

laws in a quiescent system. And further, this time interval seems sufficient to account for evolutionary changes in bacteria. Thus, the bacteria entering the outcrop may have been aerobic at the time, and are now found to be anaerobic.

It seems appropriate to discuss briefly at this point the factors which control the duration of microscopic life: (1) the food supply; (2) the source of oxygen (free or intramolecular); (3) the concentration of toxic substances which result from the life processes of the organism; (4) the temperature tolerance; and (5) the solute concentration tolerance. As discussion here of habitat conditions of the broad field of bacterial life would be irrelevant, the treatment of the subject will be confined to the premise of sulphate-reducing anaerobes being entrapped in the sediments, or of the present conditions of certain horizons from which these organisms have been isolated.

FOOD SUPPLY (SOURCE OF ENERGY AND NITROGEN)

Decomposing organic matter in nature marks the presence of microorganisms. This inanimate matter forms the source of energy and nitrogen for the microscopic life of our present seas, and it is reasonable to assume that it had the same rôle in the epeiric seas of past geological periods. After the sediments were laid down, this primordial biochemical change of fauna and flora was followed, presumably, by geophysical and geochemical changes which produced crude petroleum. If the other factors which regulate the duration of bacterial life in a system are disregarded, and the food supply is assumed to be the main regulative factor, it is seen that this final stage of the conversion of organic matter to petroleum need not mark the end of microscopic life; for it has been found that certain fungi and bacteria have the power of utilizing paraffine as a source of energy.

Buttner[1] found that mycobacteria have the property of utilizing paraffine, paraffine oil, petroleum, and sewing-machine oil as a source of energy.

Beckman[2] in 1926 contributed a preliminary observation of the effect of bacterial growth on hydrocarbon oil. He cites a particular incident of an oil cargo being wrecked in San Francisco Bay. The oil in appreciable amounts collected along the beach, but disappeared in a

[1] Hans Buttner, "A Quantitative Study of the Metabolic Products of Mycobacteria Grown upon Paraffin Media," *Arch. Hyg.*, Vol. 97 (1926), pp. 12-27.

[2] J. W. Beckman, "Action of Bacteria on Mineral Oil," *Jour. Ind. Eng. Chem.* (news edition), Vol. 4 (1926), No. 21.

rather short time. Beckman suspected that a bacterial form of life had something to do with the disappearance of this oil. He then investigated, by culturing various types of organisms in media containing a commercial grade of distillate known as E. Pale, which had a boiling point of 232° C. and a Baumé gravity of 20.8°. The source of some of the cultures was oil-soaked soil. The cultures, most of which were of the mixed type, caused a decided change in the physical character of the oil. In all media free from sulphur the Baumé gravity increased, and in the sulphur media the gravity decreased. It is his opinion that the hydrocarbons do not form a source of energy for the micro-organisms, but that the changes in the oil were caused by enzymes produced by the bacteria. It would be interesting if this phenomenon should be found to be the explanation of edge-water oil being heavier than the same oil in the center of some fields.

Fischer and Fuchs[1] report that various fungi and bacteria are able to utilize coal as a source of energy. The bacteria were cultured under aerobic and anaerobic conditions, and it was found that gases and humic acids were produced by the life processes.

This food supply which we are seeking for these anaerobes should also furnish nitrogen, for the greater part of the cells of bacteria consist of matter protein in nature. The California crudes, in particular, according to recent work of the University of Texas,[2] contain appreciable amounts of nitrogenous compounds. This work shows for the California oils, nitrogen contents ranging from 0.3 to 0.8 per cent; for Texas oils, nitrogen less than 0.1 per cent; and for the Oklahoma oils, nitrogen ranging from 0.05 per cent to 0.15 per cent. The structures of these nitrogenous compounds occurring with, or in, petroleum, have been reported as similar to pyridine or the quinolines and hydro-quinolines. This matter of nitrogen compound structure has not been definitely decided. This research of the University of Texas indicates that at least part of these compounds are not strong bases as they should be if similar to pyridine or the quinolines.

It is known that many compounds consisting of carbon, hydrogen, and oxygen, besides the carbohydrates, furnish a source of energy for many bacteria. The writer refers to such compounds as succinic acid, citric acid, tartaric acid, and various fatty acids. Work of the future

[1]F. Fischer and W. Fuchs, "Growth of Mold Fungi on Coals," *Brennstoff-Chem.*, Vol. 8 (1927), pp. 231-33 and 293-95.

[2]E. J. Poth and others, "The Estimation of Nitrogen in Petroleum and Bitumens" (University of Texas), *Jour. Ind. Eng. Chem.*, Vol. 20 (1928), No. 1, p. 83.

may show that naphthenic acids of petroleum can serve as a source of energy for the anaerobes which reduce sulphates. Exceedingly small amounts of food substances have been found sufficient for the development of certain water forms. Kohn[1] shows that certain water bacteria were able to develop in the presence of 198×10^{-10} to 198×10^{-13} per cent of glucose, 66×10^{-13} to 66×10^{-19} per cent of ammonium phosphate.

The writer has observed, in a few subsurface hydrogen sulphide waters, considerable organic matter, which was precipitated in the clear filtered sample after evaporating to a small volume in the presence of nitric acid-chlorate mixture. Simple chemical tests indicated that this organic matter was oxidized to an organic acid. The concentration of the organic matter in one particular water was at least a million times greater than the small amounts of food supplies quoted by Kohn. This fact is mentioned here for the purpose of pointing to an adequate—as far as amount is concerned—food supply in water.

It is not known to what extent the hydrocarbons and nitrogenous compounds of petroleum can serve as a source of energy and as a source of nitrogen for these specific types of sulphate-reducing anaerobes described by Beyerinck, van Delden, and Elion. These strains are now known to be few, although there are many types of bacteria which produce hydrogen sulphide as a decomposition end product from organic sulphur-bearing matter. These other types, however, do not have the power of utilizing the intramolecular oxygen of the sulphate radicle, that is, they do not produce hydrogen sulphide from sulphates.

OXYGEN SUPPLY

We are concerned only with strict anaerobes, which by definition have the power of utilizing intramolecular oxygen for the life processes. The oxygen demand of these strict anaerobes is met by the sulphate radicle; thus it seems that these organisms would cease to exist when this source of oxygen is depleted. This presupposes that these anaerobes are unable to utilize intramolecular oxygen from other sources.

ACCUMULATION OF TOXIC SUBSTANCES

Many bacteria are inhibited, and under some conditions killed, by the chemical substances which are produced by the life processes of the organisms. The degree of tolerance that these anaerobes have toward

[1]Kohn, *The Newer Knowledge of Bacteriology and Immunology* (University of Chicago Press, 1928), p. 67.

hydrogen sulphide is not known. It is reported that concentrations of 1,000 parts per million of hydrogen sulphide did not inhibit their growth in the laboratory. Rogers mentions a concentration of approximately 6,000 parts per million of hydrogen sulphide being found on the bottom of the Black Sea. The evidence in the literature indicates that these sulphate-reducing anaerobes are able to reduce appreciable amounts of sulphates through the short duration of a month. The writer would expect a limiting concentration of hydrogen sulphide at some point, leaving out of this consideration the possibility of the hydrogen sulphide reacting with minerals at such a rate as would prevent the toxic point being reached.

A water from the Permian of Crane County, Texas, at a depth of approximately 3,000 feet was found to contain 2,400 parts per million of hydrogen sulphide. The gas from this well contained 12 per cent, by volume, of hydrogen sulphide. The highest concentration of hydrogen sulphide the writer has found in a water was 600 parts per million, from a well in West Texas.

The three specific strains of anaerobes mentioned in this paper, which have been exhaustively studied in Europe, and in this country by Bastin, Gahl, and Anderson, have been found to be non-spore-bearers; thus, this unknown time period of anaerobic life in the deep subsurface horizons seems to be shortened, for no arrested stage of animation could be called upon to preserve them until earth movements, erosion, or both, brought a necessary change to their habitat.

TEMPERATURE TOLERANCE

The optimum growth temperature for non-pathogenic, non-spore-bearing organisms is fairly low, as a general rule. Two of the sulphate-reducing strains have optimum temperatures of less than body heat, but this is not the fact with one (*Vibrio thermodesulfuricans*), which as reported has an optimum temperature of approximately 50° C.

Many oil-well waters are warm, ranging in temperature from 40° to 50° C., and the temperatures of the subsurface horizons down to a minimum of 7,000 feet would not exclude the possible occurrence of these "temperature-loving" strains. Lindtrop[1] found edge-water temperatures of 87° C. in the New Grosny field, Russia.

There are, no doubt, some localities which have an excessive temperature gradient which would produce an inhibitory temperature at

[1]Norton T. Lindtrop, "Outline of Water Problems in the New Grosny Field, Russia," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), p. 1035.

7,000 feet. Further, the hot sulphur-water wells of Japan would not be expected to serve as a habitat for very many forms of life, for their temperatures are reported at the boiling point of water. It seems logical to exclude such wells and many hot sulphur-water springs of the world from the possible habitats of these sulphate-reducing microorganisms.

In connection with oil-well waters, this factor of solute concentration should, to some extent, regulate the possibilities of microscopic life. Assuming that the ions of the solute are not toxic, then some limit of total dissolved solids would be expected to prevent the growth of bacteria. It is known that many microscopic flora demonstrate a wide range of salt tolerance.

These anaerobes have been found in waters carrying approximately 60,000 parts per million of total dissolved salts. This concentration in the Mid-Continent would be considered fairly low, inasmuch as many waters have total solids ranging from 150,000 to more than 200,000 parts per million. Few highly concentrated waters carry hydrogen sulphide, and according to the writer's knowledge, few possess an appreciable amount of the bicarbonate ion; whereas hydrogen-sulphide waters ordinarily have concentrations of less than 100,000 parts per million, and bicarbonate alkalinities ranging from a few hundred to more than 1,000 parts per million. The sulphate in hydrogen-sulphide waters of the Mid-Continent is ordinarily appreciable, in contrast to exceedingly small amounts found in the highly concentrated brines of this region.

Should it be found that the high osmotic pressure of a brine similar to the water of the "Siliceous lime" in the Garber pool of Oklahoma does not prevent bacterial growth (anaerobic), then this factor of solute concentration may be abandoned.

These factors which regulate the life of micro-organisms, we may feel could not remain in balance throughout geologic periods; however, the micro-organism systems in nature seem, in general, to be at an equilibrium; that is, their rate of increase is no greater than their diminishing rate. This of course does not hold when the habitat is the intestinal tract, and the micro-organism is of a pathogenic strain.

Adherents of the theory that "petroleum and organic matter have been the active agents of sulphate reduction" have advanced the following argument against the bacteria-reduction idea. There are many types of micro-organisms in nature (soil and surface water) which produce hydrogen sulphide; thus, the observers who reported sulphate-reducing micro-organisms in oil-well waters may have been working with water

samples contaminated with surface flora. The writer, in refutation, repeats: (1) Bastin, Gahl, and Anderson did not find sulphate-reducing strains in surface or shallow ground-waters; (2) these workers used media containing only sulphate sulphur and not media containing organic sulphur compounds; (3) the large group of micro-organisms commonly found in soil and surface waters produce hydrogen sulphide in the decomposition of organic sulphur compounds, rather than from the sulphate radicle; and (4) facts which indicate that sulphates in nature oxidize inanimate organic matter are wanting.

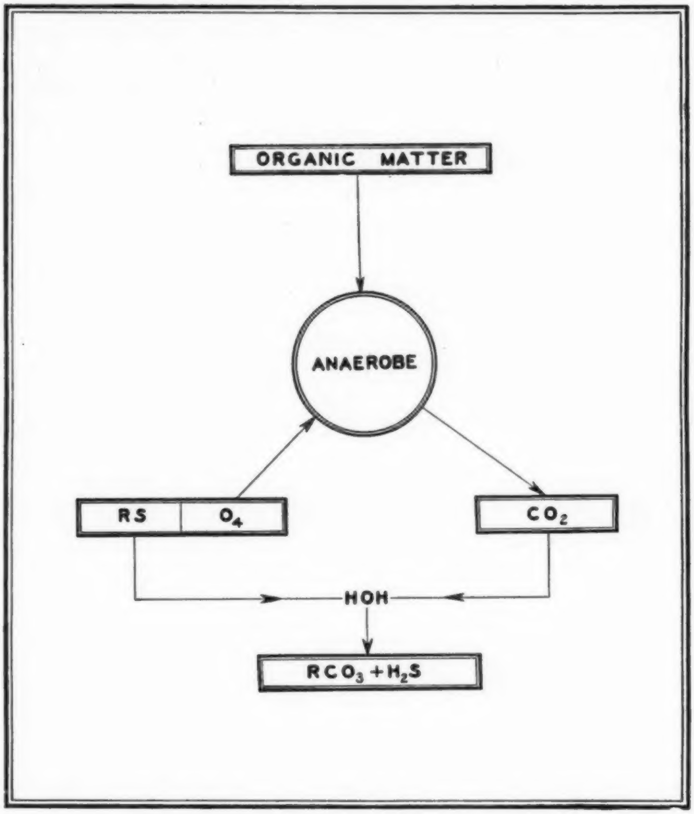

FIG. 1.—Diagram illustrating the reduction of sulphates by anaerobes.

The diagram (Fig. 1) illustrates the reduction of sulphates by anaerobes. The inanimate organic matter represents the source of energy and nitrogen; the sulphate radicle, the source of oxygen; and the carbon dioxide is a product of respiration.

CRITERIA FOR ANAEROBE PROSPECTING

The water horizons of the Mid-Continent, which offer the best opportunity for finding these or similar anaerobes, should carry hydrogen sulphide, should have bicarbonate alkalinity, not necessarily a high sulphate content, and should have a fairly low density. The horizons of this nature which have come to the attention of the writer are as follows: the Ordovician of Kansas; the Ordovician in a few townships north of the Arbuckle Mountains in Oklahoma; the Ordovician of northeast Oklahoma, near Inola and Claremore; and Permian horizons of New Mexico and Texas.

CONCLUSIONS

1. Evidence showing the reduction of sulphates by inanimate organic matter at fairly low temperatures has not been found.

2. Anaerobes which reduce sulphates have been found in oil-well waters. Seemingly the inanimate organic matter of petroleum or the carbonaceous residues furnishes the source of nitrogen as well as the source of energy.

3. The significance of this bacterial phenomenon has not been defined. When this work has been carried out more will be known about the chemical compounds which can serve as a source of energy and as a source of nitrogen for these anaerobes.

4. Many petroleum deposits may no longer be considered static chemical systems if the presence of life in many of the oil-field horizons is definitely proved.

ADDITIONAL DATA ON SULPHATE-REDUCING BACTERIA IN SOILS AND WATERS OF ILLINOIS OIL FIELDS[1]

EDSON S. BASTIN[2] and FRANK E. GREER[2]
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ABSTRACT

Evidence is presented of the occurrence of sulphate-reducing bacteria in salt waters associated with petroleum in six producing wells in the Lawrenceville, Illinois, region. Five were producing from the Bridgeport sand from depths between 900 and 1,000 feet and one from the McClosky sand at 1,850 feet. All of these brines carried hydrogen sulphide. Brines from three other oil wells were free from hydrogen sulphide and were free also from sulphate-reducing bacteria, suggesting that bacteria may play the major rôle in the formation of the hydrogen sulphide associated with the petroleum.

As bearing on the possibility of bacterial contamination of oil wells from surface sources subsequent to drilling, eight soil samples, eight fresh-water well samples and one river-water sample were collected in the Lawrenceville and Allendale regions. Seven of the eight soils and all of the fresh well waters were free from sulphate-reducing bacteria. These results lend no support to the view that the abundant bacteria of the oil-well brines came from such sources after the wells were drilled.

LAWRENCE COUNTY

In November, 1927, through the courtesy of the Illinois State Geological Survey, the senior writer was able to collect samples from oil fields near Lawrenceville, Illinois, for the purpose of perfecting new technique in studying their bacterial content and of adding to the data previously obtained from other oil wells in the state.[3] The new samples included eight from producing oil wells, six from water wells and rivers in the oil fields, and four samples of soils from the oil fields.

In preparing samples of oil-well waters for bacterial study, it had been the practice of the writers to free the samples from dissolved hydrogen sulphide before inoculation by evacuation in a sterile vacuum desiccator. This was done because a soluble iron salt (Mohr's salt) was used in the culture medium as an indicator of hydrogen sulphide developed during incubation by bacterial reduction of sulphates. If hydrogen sulphide was present to start with, the iron indicator was of course

[1]Manuscript received by the editor, November 29, 1929.

[2]The University of Chicago.

[3]Edson S. Bastin and collaborators," The Problem of the Natural Reduction of Sulphates," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), pp. 1286-93.

promptly precipitated wholly or in part on inoculation. Some of the Texas oil-field waters experimented with were so highly charged with hydrogen sulphide that evacuation even with a powerful vacuum pump failed to get rid of it. To avoid this difficulty the writers proposed to abandon attempts at evacuation, to make the first inoculations into mediums free from iron salt indicator, and then, after incubation, to make transfers to other mediums containing the indicator. The Illinois samples here reported upon were collected for the purpose of testing the value of this method, which proved to be very satisfactory.

The culture mediums used had the following composition.

		Grams
Medium 1.1 —	K_2HPO_4	0.5
	Asparagin	1.0
	Magnesium sulphate	2.5
	Sodium lactate	5.0
	Mohr's salt (ferrous ammonium sulphate)	trace
	Distilled water	1 liter
Medium 1.2 —	Same as 1.1 with 30 grams $NaCl$	

The samples are numbered so as not to duplicate the numbers of the Illinois samples previously reported upon.[1]

Since the soil and fresh-water samples contained no hydrogen sulphide, inoculations were made directly from them in duplicate into the non-salt medium 1.1 containing iron salt as indicator. The results are here reported in detail.

Soil samples.—Numbers 31, 32, 33, and 34 are soil samples taken from road cuts in the Lawrenceville district, but far enough from any oil well to avoid contamination from the wells. The exact localities are as follows: Numbers 31, 32, and 33, reddish soils from depths of 3 feet in road cuts 5 miles north, 3 miles northwest, and 2 miles north of Lawrenceville, respectively; and No. 34, black soil from road ditch ¼ mile east of farm of Carl Lewis, where fresh-water sample No. 35 was taken.

Samples were collected on November 10, 1927, and inoculated on November 12. Numbers 31, 32, and 33 after 17 days showed no black precipitate; hence, contained no sulphate-reducing bacteria. No. 34 after 9 days showed a slight black precipitate which by the 17th day had be-

[1] *Op. cit.*, pp. 1290-91.

come abundant. Sulphate-reducing bacteria were therefore present in this one soil.

Fresh-water samples.—Six samples of fresh surface or shallow well waters were collected as follows.

No. 35. Water from dug well 26 feet deep (the last 7 feet in sandstone) on farm of Carl Lewis, T. 4 N., R. 12 W.

No. 36. Bowers and Ross' No. 3 water well. Depth, 350 feet.

No. 37. Bowers and Ross' No. 2 water well. Depth, 350 feet. From bleeder valve of pump jack.

No. 38. Water well. R. Sumner Power No. 559, Ohio Oil Company. Depth, 212 feet. From bleeder valve of pump jack.

No. 39. Embarrass River, near Lawrenceville.

No. 40. Drinking-water well on Silurian Oil Company's Crump 40, Sec. 19, T. 4 N., R. 12 W. Depth, 151 feet. From bleeder valve of pump jack.

Of the six fresh-water samples the five from wells gave negative results. The single sample of river water (No. 39) showed after 6 days a black precipitate in one of the duplicate inoculations, but negative results even after 17 days in the other. Sulphate-reducing bacteria were therefore present sparingly in the river water. As the river drains a part of the oil fields, the possibility of contamination from oil-well waters is not excluded. It should be noted, however, that transfers from the first culture of No. 39 into Mediums 1.1 and 1.2 gave black precipitate in 1.1 (without salt), but not in 1.2 (with salt), suggesting that the sulphate-reducing organism was adapted to a fresh-water and not to a salt-water habitat.

Oil-well waters.—Nine samples (Numbers 41 to 49 inclusive) of salt water were collected from producing oil wells in the same region near Lawrenceville from which the soil and fresh-water samples were taken. These waters were tested qualitatively in the field for hydrogen sulphide by lead acetate solution and for sulphates by barium chloride. Salty taste was also noticed. The wells sampled were as follows.

No. 41. Silurian Oil Company's Crump No. 2, Sec. 19, T. 4 N., R. 12 W. Depth, 922 feet. Pumping 24 hours. Producing from Bridgeport sand. Salty. Some sulphates and hydrogen sulphide.

No. 42. Silurian Oil Company's Crump No. 3, Sec. 19, T. 4 N., R. 12 W. Pumping period, 10 hours. Sample from bleeder valve. Depth, 925 feet. Producing from Bridgeport sand. Salty. Carries hydrogen sulphide. Low in sulphates.

No. 43. Silurian Oil Company's Crump No. 5, Sec. 19, T. 4 N., R. 12 W. Pumping 24 hours. Sample from end of 50-foot lead line. Depth, 928 feet. Producing from Bridgeport sand. Salty. Small amounts of sulphates but no hydrogen sulphide present.

No. 44. Silurian Oil Company's Crump No. 14, Sec. 19, T. 4 N., R. 12 W. Depth 902 feet. Pumping period, 14 hours. Producing from Bridgeport sand. Salty. Small amounts of sulphates but no hydrogen sulphide present.

No. 45. Silurian Oil Company's Crump No. 19, Sec. 19, T. 4 N., R. 12 W. Pumping 24 hours. Depth, 920 feet. Producing from Bridgeport sand. Salty. Some sulphates and hydrogen sulphide present.

No. 46. J. D. Bowers' No. 10, Sec. 29, T. 4 N., R. 12 W. Depth, 971 feet. Producing from Bridgeport sand. Pumping period, 10 hours.

No. 47. J. D. Bowers' No. 14, Sec. 29, T. 4 N., R. 12 W. Depth, 962 feet. Producing from Bridgeport sand. Pumping period, 7 hours. Salty. Only traces of sulphates. Hydrogen sulphide present.

No. 48, Bowers and Ross' No. 19, Sec. 29, T. 4 N., R. 12 W. Depth, 1,855 feet. Pumping period, 18 hours. Producing from McClosky sand. Very salty. Sulphates low. Hydrogen sulphide present.

No. 49. Ohio Oil Company's Tanquarry No. 5. Probably in Sec. 28, T. 4. N., R. 12 W. Sumner Power No. 559. No sulphates or hydrogen sulphide present.

All these waters were inoculated in duplicate into salty Medium 1.2, *from which, however, the soluble iron salt indicator had been omitted*. In the absence of the indicator no black precipitate, of course, developed, but bacterial growth was betrayed in some samples by the development of marked turbidity, by gas development, and by the formation of gray bacterial films on the tube walls. The cultures were limpid at first.

Numbers 41, 42, and 45-48, inclusive, all showed evidence of bacterial growth by turbidity, gas development, or gray films, and at the end of 17 days transfers were made from these cultures to Mediums 1.1 and 1.2 *with* the soluble iron salt indicator to determine whether the bacterial growths included sulphate-reducing forms. In all except No. 48 black precipitates were observed at the end of 24 hours when the first reading was made. In No. 48 black precipitates were present at the end of 3 days when the second reading was made. All six of these oil-well brines therefore carried sulphate-reducing bacteria apparently in abundance. It is noteworthy that all except No. 48 developed black precipitates in both the fresh medium (1.1) and the salt medium (1.2) whereas No. 48, which was noted in the field as a particularly strong brine, developed black precipitates only in the salt medium.

It is especially noteworthy that Numbers 43, 44, and 49, which showed no evidences of bacterial growths in the first set of cultures (without iron indicator), were the only oil-well waters that failed to give a field test for hydrogen sulphide with lead acetate solution. These, because of their freedom from hydrogen sulphide, were inoculated directly into Medium 1.2 with iron indicator, but even at the end of 17 days failed to develop any black precipitate. Sulphate-reducing bacteria were seemingly absent, therefore, from these three waters.

ALLENDALE FIELD, WABASH COUNTY

As reported in the earlier article already referred to,[1] only one sample of salt water from oil wells in the Allendale field has been tested for sulphate-reducing bacteria; in this they were found to be present. This sample came from the Bridgeport-Marcotte well No. 2 in Sec. 24, T. 1 N., R. 12 W., which was 1,115 feet deep and producing from the Bridgeport sand of Pennsylvanian age. In view of the abundance of these bacteria in the Bridgeport sand a few miles north in the adjacent Lawrence County, it is probable that they are also prevalent in the Allendale field.

To test the probability of the bacteria of the oil-producing wells having been introduced from soils and surface waters after the wells were drilled, Gail Moulton, of the Illinois Geological Survey, forwarded to the writers four samples of soils and three samples of fresh well waters, all from within the limits of this field. Locations and descriptions of these samples follow.

Water No. 1. Water well 40 feet deep on farm of J. W. Price, SW. ¼, Sec. 19, T. 1 N., R. 12 W.

Water No. 2. From well about 50 feet deep on Fox farm in NE. ¼, Sec. 1, T. 1 N., R. 12 W.

Water No. 3. From well probably 20 feet deep at Drennen School in SW. ¼, Sec. 1, T. 1 N., R. 12 W.

Soil No. 1. Yard near house of J. W. Price, SW. ¼, Sec. 19, T. 1 N., R. 12 W. From depth of 2½ feet.

Soil No. 2. Cultivated field on Fox farm in NE. ¼, Sec. 1, T. 1 N., R. 12 W. From depth of 2-2½ feet.

Soil No. 3. 300 feet south of Soil No. 2, in cultivated field. From depth of 3 feet.

Soil No. 4. 300 feet west of Drennen School, SW. ¼, Sec. 1, T. 1 N., R. 12 W., from spot which did not appear to have been cultivated. From depth of 3-4 feet.

[1] *Op. cit.*, pp. 1290-91.

The samples were collected in sterile glass bottles and inoculated in duplicate into Mediums 1.1 (without salt) and 1.2 (with salt), following the methods described in the paper previously cited. Even after 10 days in the incubator none of these samples showed any black precipitate and sulphate-reducing bacteria seem, therefore, to have been absent.

These results, although not definitely excluding the possibility of bacterial inoculation of the oil-producing horizons from surface sources after the wells were drilled, offer no support to this view.

CONCLUSIONS

Evidence is presented of the occurrence of sulphate-reducing bacteria in brines associated with petroleum in six wells not previously sampled in the Lawrenceville region, Illinois, five producing from the Bridgeport and one from the McClosky sands from depths between 900 and 2,000 feet. All of these waters gave field tests for hydrogen sulphide.

Three brines which gave no field test for hydrogen sulphide were the only oil-well samples that failed to show sulphate-reducing bacteria, suggesting that bacterial reduction of sulphates is a major source of this gas. This conclusion must, however, be tentative until checked by a larger number of observations.

Soils and shallow sources of fresh water within the Lawrenceville and Allendale areas were tested for sulphate-reducing bacteria in view of the possibility of inoculation of the wells from such sources subsequent to drilling. The absence of sulphate-reducing bacteria from all eight fresh-water wells and from seven out of eight of the soil samples gives little support to the view that the abundant bacteria of the oil-well brines came from surface sources subsequent to drilling.

In No. 28, the one soil sample carrying sulphate-reducing bacteria, transfers from the first culture medium into Mediums 1.1 (without salt) and 1.2 (with salt) gave a black precipitate only in the *salt-free* medium. Transfers in duplicate from the first cultures of No. 48 from the McClosky sand and much the most saline of the oil-well brines, into Mediums 1.1 and 1.2 gave a black precipitate only in the *salt* medium. These results suggest a certain amount of adaptation of the sulphate-reducing bacteria to the degree of salinity of the water. Attention should be directed in this connection to the paper by Gahl and Anderson in which the samples of California oil-field waters originally collected and studied by Bastin and Anderson were submitted to more elaborate bacteriological

investigation.[1] It is significant that the bacteria that they found to be able to live in cultures at 50° C. came in general from the wells that in the field showed the highest temperatures (44°-47° C.), suggesting a temperature adaptation to their environment.

[1]Rudolf Gahl and Belle Anderson, "Sulphate-Reducing Bacteria in California Oil Waters," *Centralblatt für Bakteriologie*, et cetera, Bd. 73 (1928), pp. 331-8.

PERMIAN STRUCTURE AND STRATIGRAPHY OF NORTH-WESTERN OKLAHOMA AND ADJACENT AREAS[1]

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Enid, Oklahoma

ABSTRACT

Some problems involved in Permian stratigraphy relating particularly to exposures in northwestern Oklahoma and adjacent areas are discussed in this paper. Variability, such as lateral and vertical changes in section, has been noted. Striking examples of dip and fold are known to occur. Permian beds have been mapped and the attitude of certain beds with respect to sea-level has been indicated. Conclusions in correlation, in geologic history, and in regional interpretation have been stated for the area along the northern limb of what is now known as the Anadarko basin.

INTRODUCTION

The geology of northwestern Oklahoma and adjacent areas in Kansas and Texas has only recently been the object of an awakened interest, due chiefly to the endeavor of oil-producing companies and individuals to acquire possibly productive acreage for oil and gas. Many geologists have gone into the area to study and survey, especially the Permian exposures, to find evidences of structure as a basis upon which to acquire oil and gas leases. The writer, in common with others, has pursued an extended as well as intensive study of Permian horizons. Some new phases of Permian geology have been observed. It is therefore the writer's purpose in this paper to enumerate the more pertinent of these phases, not so much in the hope that this enumeration may be a contribution to our knowledge of Permian geology, but rather that it may be a step in furthering a progressive study of the Permian horizons and their problems, as we find them in the field, along the northern limb of the Anadarko basin.

ACKNOWLEDGMENTS

To the many geologists who have studied the Permian areas included in this paper the writer is especially indebted. In any discussion of this type it is difficult to give proper acknowledgment to every geologist who

[1]Manuscript received by the editor, December 13, 1929.

[2]Geologist, Champlin Refining Company.

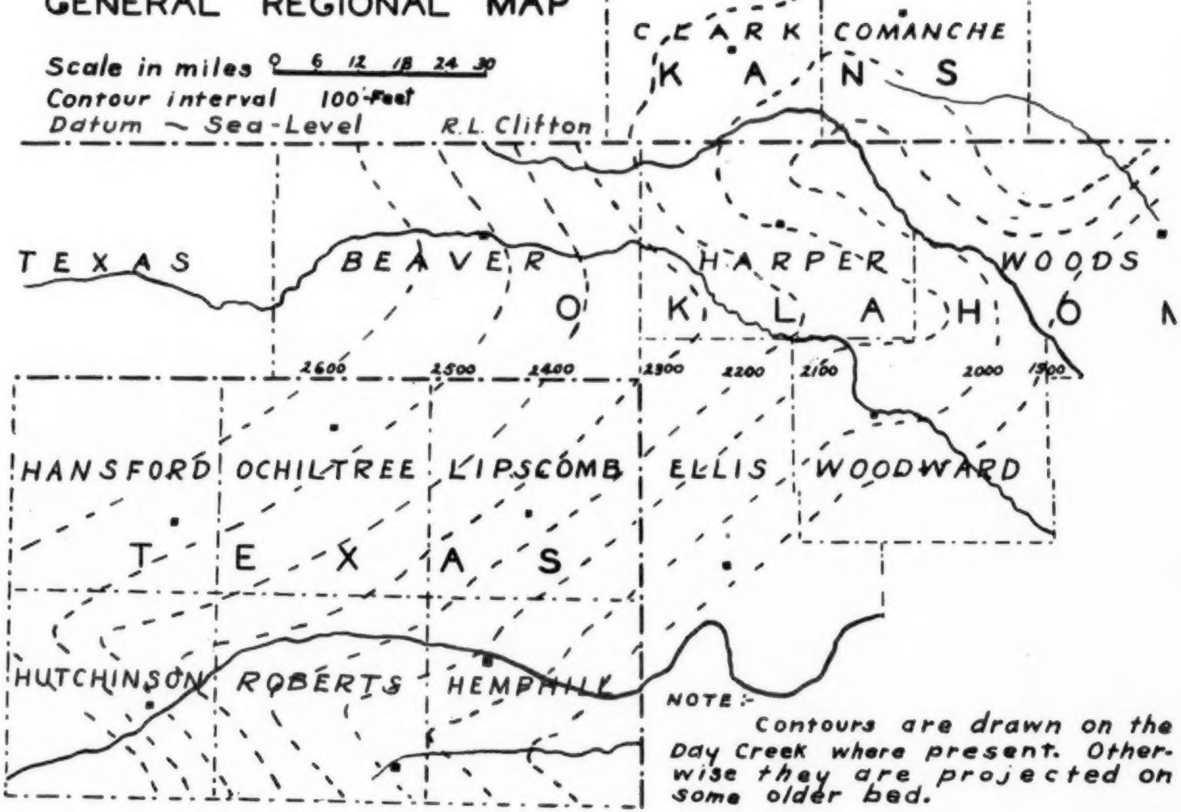
GENERAL REGIONAL MAP
Scale in miles 0 6 12 18 24 30
Contour interval 100 Feet
Datum ~ Sea-Level
R.L. Clifton
CLARK
COMANCHE
K A N S
TEXAS
BEAVER
HARPER
WOODS
O K L A H O M
2600
2500
2400
2300
2200
2100
2000
1900
HANSFORD
OCHILTREE
LIPSCOMB
ELLIS
WOODWARD
T E X A S
HUTCHINSON
ROBERTS
HEMPHILL
NOTE:-
Contours are drawn on the Day Creek where present. Otherwise they are projected on some older bed.

FIG. 1

has in some manner contributed to the fund of information upon which the writer draws. Communications, oral and otherwise, with geologists, in addition to the published literature, have served the writer well. A bibliography is included.

REGIONAL STRUCTURE

In general the regional physiographic and structural features in northwestern Oklahoma and the adjacent areas may be described as representing a monocline sloping southward toward the Wichita Mountains and the buried Amarillo uplift. There is, however, a local modification of this general expression. Extending northwest and southeast through the counties of Beaver, Harper, and a part of Woodward, there is an area of Permian exposures occurring at decidedly higher elevations than do the same formations on either flank of this regional feature.

LOCAL DIPS AND FOLDS

The occurrence of many local folds or deformations is one of the intricate problems of Permian geology in this area. Many folds whose relief or closure is as much as 75 feet or more, have been observed in more or less localized areas, and erratic dips, that produce as it were pseudo-structures, are found to be of common occurrence. Many of the folds resemble symmetrical anticlines, showing no erratic or irregular dips in their configuration. The question may be asked, is the folding deep-seated in origin, or is it superficially induced, perhaps by chemical and physical changes in underlying precipitate beds?

INTERPRETATION OF FOLDS

Economic as well as geologic importance is involved in any problem of structure. Naturally the concern in northwestern Oklahoma centers on the questions (1) what is structure, in the sense of deep-seated folding?—and (2) what is simulated structure, in the sense of superficial, or pseudo-folds? The writer suggests that the dips and folds in this area—whatever their type—may be caused by (1) solution or change in the underlying beds, modifying the cubical space of the beds, or (2) forces of folding, originating in deep-seated horizons.

Underlying the Permian exposures of northwestern Oklahoma there is a considerable section composed of large amounts of salt, gypsum, anhydrite, and limestone. If solution has changed the cubic volume of any precipitate bed, for example, the salt horizon, the surface expression of this change would most probably be a series of erratic folds and dips, for the reasonable probability is that the chemical and physical forces of

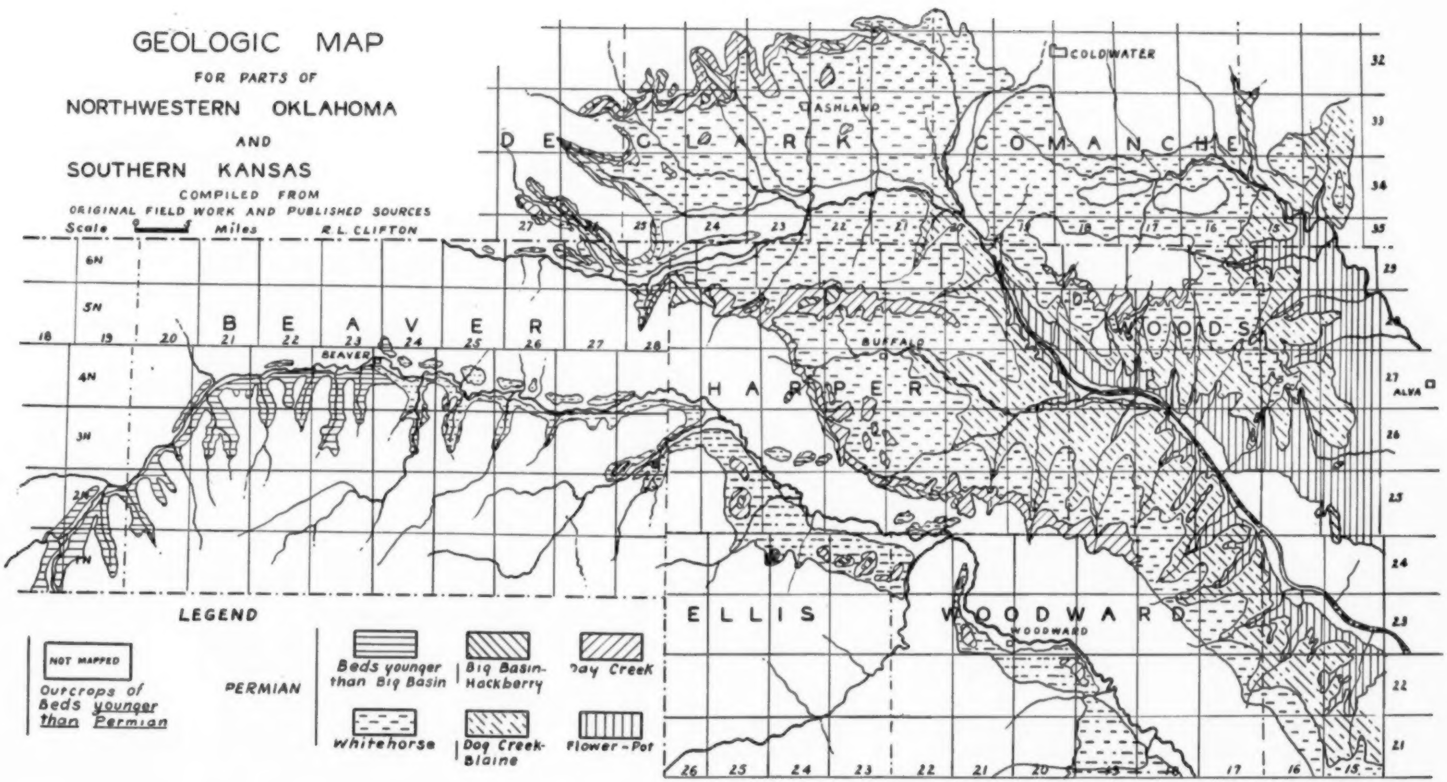
GEOLOGIC MAP
FOR PARTS OF
NORTHWESTERN OKLAHOMA
AND
SOUTHERN KANSAS
COMPILED FROM
ORIGINAL FIELD WORK AND PUBLISHED SOURCES
Scale Miles R. L. CLIFTON
BEAVER
HARPER
ELLIS
WOODWARD
WOODS
COMANCHE
CLARK
COLDWATER
ASHLAND
BUFFALO
ALVA
LEGEND
NOT MAPPED
Outcrops of Beds younger than Permian
PERMIAN
Beds younger than Big Basin
Big Basin-Hackberry
Day Creek
Whitehorse
Dog Creek-Blaine
Flower-Pot

FIG. 2

solution would operate throughout an extended area in a differential rate and degree. Thus, a subsurface precipitate bed or beds would be expected to undergo a greater degree of volume or cubic change at one point than at some other. Any change, therefore, in the cubic content of the underlying precipitate beds would result in overhead slumping, the surface expression of which would most probably be irregular dips and superficial or pseudo-folds.

On the other hand, it is admitted without argument that evidences of deep-seated folding exist in this area. There is a regional tilting of the beds. Some of the more nearly symmetrical anticlines or folds occurring here may have been formed by deep-seated forces, rather than by the forces of solution and change in the precipitate section. The writer has no geologic proof that the forces of solution will of themselves produce approximately symmetrical folds. However, the operation of the law of chance may be competent to account for the few folds that approach the normal type of deep-seated origin. In view of the number of folds that approach the normal type and which exhibit no erratic dips, it seems to the writer that the forces of solution alone are not competent to account for all of the anticlinal folds in this area. Some of them should be classified as belonging to the normal structural type of deep-seated origin.

AGE OF LOCAL FOLDS

Evidences in the field indicate that some of the local dips and folds exhibited by Permian beds were initiated previous to Comanche, or Lower Cretaceous, time. Rocks of Comanche age are present as more or less detached outcrops or erosional remnants in parts of Kansas and Oklahoma. Fortunately, a few of these Comanche outcrops overlie Permian beds that locally exhibit marked dips and folds. At one of these localities in Sec. 14, T. 25 N., R. 22 W., it was noticed that the Comanche beds, although reflecting the normal monoclinal tilting for that area, did not reflect the local dips and folds exhibited in the Permian beds.

STRATIGRAPHY

It may be stated again that the Permian outcrops on the north flank of the Anadarko basin (11)[1], ranging from the oldest to the youngest, belong to the Chickasha (11), or Flower Pot (6), the Blaine (10), the Dog Creek (6), the Whitehorse (10), the Day Creek (6), the Hackberry

[1]Numbers in parentheses refer to publications listed in the Bibliography at the end of this paper.

(6), and the Big Basin (6) horizons. Overlying the Big Basin in the western part of this area is a series of beds belonging to some part of the Cloud Chief (11).

As these horizons have been previously described, it is the writer's purpose to enumerate only those geologic phases that may contribute additional data to our present knowledge concerning the Permian beds of northwestern Oklahoma and the adjacent areas. It is not his purpose in this paper to discuss beds older than the Blaine formation.

BLAINE FORMATION

As the Blaine formation has been described by both Gould (10) and Cragin (6), no reference need be made here to the formation except to state that southwestward there is a marked thickening of the formation; also, at one locality in southeastern Harper County, Oklahoma, four distinct beds separated by shale intervals 5 feet or more in thickness have been observed. The increase in thickness and the increase in the number of gypsum beds may be due in part to some changes in the overlying formation.

DOG CREEK SHALE

The Dog Creek shale (6), as previously described by Cragin and later by Gould, presents a few good outcrops in Woods, Woodward, and Harper counties in Oklahoma. The formation undergoes changes both in its lithologic character and in its thickness southwestward. No thickness greater than 25 feet has been observed in Harper County, Oklahoma.

Within the formation in Woods County, Oklahoma, are two or more discontinuous beds of dolomite. Westward these lenses are very largely displaced by gypsum. This lithologic modification renders it difficult to differentiate between Blaine and Dog Creek. Two beds of gypsum have been observed within the Dog Creek,—or in beds occupying the stratigraphic position of the Dog Creek, in southeastern Harper County, Oklahoma. Seemingly the Dog Creek gradually thins southwestward, or rather experiences a lateral gradation into the Blaine.

If geologic formations are to be classified on stratigraphic resemblances, the writer believes that the Dog Creek shale should be classified and correlated as a part of the Blaine formation in Kansas and Oklahoma, since no definite Dog Creek beds have been recognized in Texas. Attention has been called previously to this same point by Lloyd and Thompson (17). However, under present practices in nomenclature, a formation name should not be re-defined to include more than its original

definition. Nevertheless, evidences in the field seem to indicate that the formation name Blaine should be dropped and some new formation name adopted to include what now comprises the Blaine and Dog Creek beds.

Throughout the area of northwestern Oklahoma, as pointed out by Beede, the zone of unconformity—or, as the writer believes, a series of local unconformities—at the Dog Creek-Whitehorse contact is in evidence. It is possible that the zone of unconformity itself may have controlled the changes in thickness of the Dog Creek shale, at least locally.

WHITEHORSE SANDSTONE

In general the Whitehorse (9) sandstone must be regarded as a series of depositional units, rather than as a simple sandstone formation. A detailed survey of its exposed sections in many localities shows that the Whitehorse includes horizons of massive fine-grained sandstone, shale beds, sandy shale beds, at least five gypsum or gypsiferous beds or lenses, and five or more fossiliferous lagoonal or shore-line or channel-like sandstone deposits.

Approximately 30-40 feet below the base of the Day Creek occurs a bed of massive fine-grained sandstone, 20-30 feet thick, which is continuous throughout wide areas. Due to its coloration, its peculiar type of weathering, its mineral content, and its bedding, this horizon is easy to recognize in widely separated areas of exposure.

The problem of the gypsum beds or lenses within the Whitehorse again supports the view that the Whitehorse horizon is a collection of stratigraphic units, some of which are merely local lenses, or discontinuous beds, although others are continuous throughout wide areas.

At least three of the gypsum lenses or units are continuous throughout more than local areas. In this connection it should be stated that in the shoreward areas of Whitehorse deposition, its outcrops do not show the presence of definite gypsum beds. It is commonly in those areas where erosion has cut deeply into the Whitehorse section that the gypsum beds or lenses are conspicuous at the outcrop. The exposures in Woods County, Oklahoma, and in Clark County, Kansas, show no gypsum lenses of more than a foot in thickness. There is here, instead, much satin spar in definite sections of the horizon. It is in the outcrops of the Whitehorse in Harper, Woodward, and Beaver counties that the gypsum horizons become conspicuous. By way of digression, it may be stated with propriety that gypsum lenses have been observed in the Whitehorse horizon in Grady County, Oklahoma, and in certain of the Texas exposures.

In general the gypsum lenses within the Whitehorse appear at approximate stratigraphic positions. Eighty or ninety feet below the base of the Day Creek there is a bed of gypsum, 2-6 feet in thickness. Excellent outcrops of this horizon are observed in Harper and Woodward counties in Oklahoma. In Sec. 14, T. 25 N., R. 22 W., an exposure of the Whitehorse presents an ideal view of the stratigraphic relationship of this and other lower gypsum beds.

At approximate distances of 125 feet and 160 feet below the Day Creek, other gypsum beds, 1-7 feet in thickness, appear in the geologic section. These beds are to be observed in outcrops in various parts of southern Harper and northern Woodward counties in Oklahoma.

In the lower part of the Whitehorse section at least two zones of gypsum beds, or lenses, have been observed. A persistent zone of gypsum appears at or near the base of the Whitehorse. Excellent exposures of this bed occur in southeastern Harper County, Oklahoma.

Approximately 40-50 feet above the basal Whitehorse, a rather persistent gypsum horizon of two or more lenses has been found in this area. This gypsum zone, with its interbedded sands and shales, is approximately 30-40 feet thick. Convenient exposures of this zone occur in Harper County, Oklahoma. For example, 2 miles east of Buffalo in Sec. 8, T. 27 N., R. 22 W., and northwest of Buffalo, outcrops of this gypsum zone are found.

A considerable area of gypsum crops out in T. 3 N., R. 24 E., on Clear Creek in Beaver County, Oklahoma. The thickness of this section, of four or more gypsum beds, with the interbedded red shale beds, is approximately 40-50 feet. The stratigraphic position of this gypsum horizon is regarded by the writer as being at the top of the Whitehorse, in that section above the characteristic massive sandstone, and in the zone of local unconformity below the Day Creek. It is possible that the upper part of this gypsum section is the stratigraphic equivalent of the Day Creek. Younger beds, appearing at the surface east of the gypsum outcrops, have been correlated by the writer as belonging to the Big Basin sandstone.

The Whitehorse horizon offers to the geologist a varied depositional history,—a history that involves, in a small way, every phase of the geological gamut as to the origin of its sediments, ranging from continental, or partly continental, to marine or modified marine deposition. Extremes in climate accompanied extremes in deposition.

A very interesting type of depositional history is seen in the so-called channel sandstones that occur at different horizons within the

Whitehorse. At this date no less than five widely separated occurrences of these lagoonal or shore-line phases of deposition have been delineated by the writer and others. These deposits are ordinarily fossiliferous. Their chief occurrences are in Woods County, at Whitehorse Springs and southwestward; in Grady County, near the town of Verden and southeastward into Stephens County; in northern Woodward County, on Chimney Creek; and 4 miles east of Woodward, on the south bank of North Canadian River. All of these localities are in Oklahoma. In Texas the chief localities of similar beds occur in Collingsworth County near the old Dozier Post Office and in Hall County near Memphis and southward. From all of the localities the writer has collected many marine invertebrate fossils of a few species. By way of digression, it may be added that most of the same species have been collected from Permian horizons in different localities of New Mexico, and in southwest Texas. Some of these species are no doubt diagnostic for correlation purposes.

The presence of fossils in certain beds of the Whitehorse (first noticed by Gould and first studied by Beede) has occasioned much investigation and study. The writer believes that antecedent to Whitehorse time much of the shoreward area of Blaine deposition, due to the retreat of the sea, became land, and was subjected to erosion. Then following the beginning of Whitehorse time the advancing sea, or rather oscillating sea, again overspread the land, and again for a time occupied the shallow depositional basins, probably comparable with lakes and lagoons and shallow arms of the sea. These oscillations of the sea in areas of Whitehorse deposition continued through the greater part of Whitehorse time and in their more or less limited incursions into the area of Whitehorse deposition they carried a fauna to its basins.

This fauna, able to exist only for a short time against the rigor of climatic extremes, would most probably be limited in its distribution in the depositional areas.

The channel-like fossiliferous beds occur, stratigraphically, from 40 feet to as much as 250 feet above the base of the Whitehorse. In Woods County, Oklahoma, the fossiliferous beds occur, approximately, from 50 to 100 feet above the base of the Whitehorse. In Grady County, Oklahoma, the channel-like beds occur approximately 40 feet above the base of the Whitehorse. The fossiliferous beds here are stratigraphically above the lowest gypsum bed in the Whitehorse. East of Woodward, Oklahoma, the fossiliferous beds occur approximately 140 feet above the base of the Whitehorse. In the Texas localities, the fossiliferous

channel-like beds occur from approximately 150 to 250 feet (17) above the base of the Whitehorse. The maximum may be seen at the locally designated Dozier Mounds, and the minimum is found south of Memphis, Texas.

The Whitehorse horizon, with its variation in depositional phases, presents at best an anomalous geologic unit. Perhaps it should be considered as more than one formation. Yet to do so is to meet other and even greater geologic obstacles. It seems to the writer, therefore, that the Whitehorse may best be considered as a division made up of two or more persistent members and perhaps several local or discontinuous members.

DAY CREEK DOLOMITE

The principal areas of the Day Creek (6) exposures occur in Clark County, Kansas, and in Woodward, Harper, and Woods counties, Oklahoma. Isolated outcrops of the formation also occur in Meade County, Kansas, and Beaver and Ellis counties, Oklahoma.

In lateral extent the Day Creek differs in mineral content. Originally described as a dolomite, the Day Creek shows wide lateral variations. In the shoreward areas of its deposition the beds consist of an approximate dolomite,—at least, calcium and magnesium carbonates both are present. Chert or flint occurs as an important secondary constituent. Basinward the dolomite or carbonate gives way to the sulphate, gypsum. The chert content decreases or entirely disappears. Evidently there is some relationship between the presence in the formation of dolomite and chert and proximity to the shore line of the Day Creek sea. Lateral lithologic changes, such as the presence of much gypsum in the Day Creek basinward, seem to support this theory.

Throughout the area of its outcrops, the Day Creek contains small amounts of malachite, or copper compound. While this factor can not be regarded as a definite diagnostic criterion in correlation, it nevertheless may be used as an aid in recognizing the horizon of the Day Creek at the outcrops on the southwest. However, it should be mentioned in this connection that there are thin dolomite lenses in the upper Whitehorse, and above the Day Creek itself, that contain traces of a copper compound.

For some time the evidence has been accumulating to support the conclusion that there is an unconformity, or series of local unconformities, within the approximate 20-foot zone immediately below the base of the Day Creek. Between the top of the uppermost massive sandstone bed,

near the top of the Whitehorse and the base of the Day Creek, there is a 30-40-foot section, the upper part of which is a zone of unconformity or perhaps a series of local unconformities. The variability in the character, in the coloration, and in the mineral content, of the sediments in this zone suggests at least a brief stratigraphic break in depositional sequence. At one locality in the east half of Sec. 12, T. 25 N., R. 21 W., the presence of a thin but coarse sandstone bed, 1 foot thick, has been observed. Immediately above this sandstone occurs a bed of sand intermixed with a mudstone conglomerate. At other localities the writer has noticed a decided thinning in the 30-foot section, below the Day Creek. This thinning can not be attributed entirely to solution or slumping if the position of the Day Creek and overlying beds is considered. In many places, however, this zone is much influenced by the forces of erosion, and it is not uncommon to find the harder Day Creek dolomite let down by the forces of erosion to rest on the upper massive sandstone at the top of the Whitehorse.

HACKBERRY SHALE

Above the Day Creek there is a zone of red shale which is gypsiferous in its upper part. This horizon, originally described by Cragin (6), has typical exposures in Harper and Beaver counties in Oklahoma and in Clark and Meade counties in Kansas. Exceptionally good sections of this horizon may be observed in Sec. 18, T. 26 N., R. 23 W., and in Sec. 1, T. 28 N., R. 26 W., Harper County, Oklahoma.

BIG BASIN SANDSTONE

Above the Hackberry shale as defined by Cragin (6) occurs a series of sandstones, ordinarily of two or three beds, separated by thin beds of dark red shale. In many places these shale beds exhibit a brilliant maroon and white color contrast. At some localities the sandstones are parti-colored or variegated, in an irregular or blotched maroon and white color effect. Commonly, gypsum veins, obliquely and variously arranged in the shales and sands, are present, giving a peculiar character to the exposed beds.

At Cragin's type locality for the Big Basin sandstone in Clark County, Kansas, the two-color effect of maroon below and white above, is a striking feature of these deposits on the east rim of the Big Basin, the depression from which the sandstone takes its name. However, the color contrast exhibited at this point is only poorly approximated at any other outcrop of the sandstone studied by the writer. It is suggested

that percolating or surface waters at the type locality may have greatly influenced the coloration of the sandstone. Less than a mile southeast of the type section, the Big Basin sandstone exposures do not approximate the coloration at the type locality.

Throughout this area, a few sections of the Big Basin sandstone are excellently exposed; for example, 6 miles west of Ashland, Kansas, the sandstone is in proper sequence with underlying beds, extending to the top of the characteristic massive sandstone in the Whitehorse; also in Sec. 18, T. 26 N., R. 23 W., and in Sec. 1, T. 28 N., R. 26 W., in Harper County, Oklahoma, are excellent exposures of the Big Basin. At each of these localities a well-exposed Permian section of 150 feet or more in thickness may be observed.

BEDS ABOVE BIG BASIN SANDSTONE

In parts of Harper and eastern Beaver counties, Oklahoma, and in parts of Clark and Meade counties, Kansas, there is a section above the Big Basin sandstone ranging in thickness from a few feet to 30 feet. These beds consist of dark red shales, sandy shales, and fine-grained sandstones. In many places this horizon is gypsiferous.

In Beaver County, Oklahoma, west of R. 24 E., the section above the Big Basin increases notably in thickness westward. These younger beds are perhaps referable to the Cloud Chief (11). However, it is quite possible that the uppermost beds in the western part of the county should be referred to horizons younger than the Cloud Chief.

SUGGESTED CHANGES IN NOMENCLATURE

The Cloud Chief (11) as originally defined by Gould includes the Permian beds from the top of the Day Creek up to the base of the Quartermaster formation. Evidences in the field suggest that the Cloud Chief is not a geologic unit, but rather that it represents a group of more or less continuous stratigraphic units. The writer believes that the Cloud Chief as a formation name should be dropped and that another formation name should be adopted to include the beds from the base of the Day Creek up to the base of the Quartermaster. There is some evidence to suggest that even the Quartermaster might well be included in this suggested revision. At any rate, a new formation to include the Day Creek, the Hackberry, the Big Basin, and the Permian beds overlying the Big Basin, up to the base of the Quartermaster, seems necessary if geologic designation is to be more strictly applicable to northwestern Oklahoma and adjacent areas.

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MAGNETOMETER STUDY OF THE CADDO-SHREVEPORT UPLIFT, LOUISIANA[1]

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ABSTRACT

Major disturbances of the vertical magnetic field are associated with the Caddo-Shreveport uplift. The writer presents the relationship between geologic structure and the vertical element. The possibility of well casing and tubing introducing a distortion of the lines of force delineating the field is considered, and the similarity of vertical intensity and gravity gradient profiles is suggested. The writer offers several hypotheses to account for the areal pattern of the resultant anomalies.

The Caddo-Shreveport uplift has been chosen as a subject for this study on account of its geologic proportions as well as the magnitude of the magnetic anomalies within the area. From careful surveys conducted by the writer it has been found that this uplift causes a greater magnetic disturbance of the vertical field than any other oil- and gas-producing region in the western or central parts of northern Louisiana.

LOCATION

The Caddo-Shreveport uplift is located on the northern end of the Sabine uplift in Caddo Parish, in northwestern Louisiana. It has an areal extent of approximately 1,000 square miles.

PRODUCTION

Figure 1 indicates the producing areas in the region. An examination reveals that oil and gas production occurs on the north end in the Caddo and Pine Island fields, and gas production on the southwest and southeast flanks in the Waskom and Shreveport districts respectively. The recently discovered Dixie field produces oil on the east-central edge of the uplift.

STRUCTURE

The structural details of the uplift are shown in Figure 2, which has been contoured on an interval of 50 feet, the contours being drawn on top of the Nacatoch formation of the Upper Cretaceous. This figure

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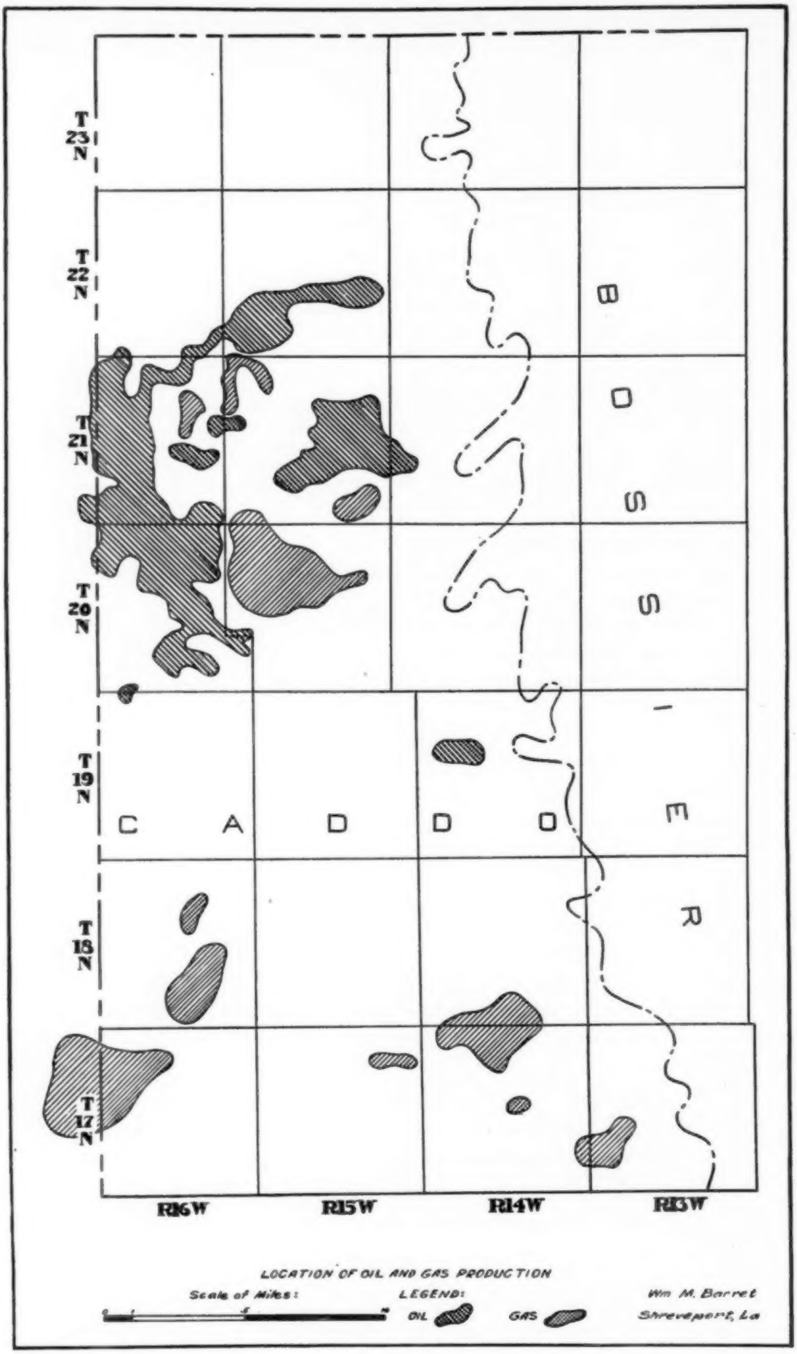
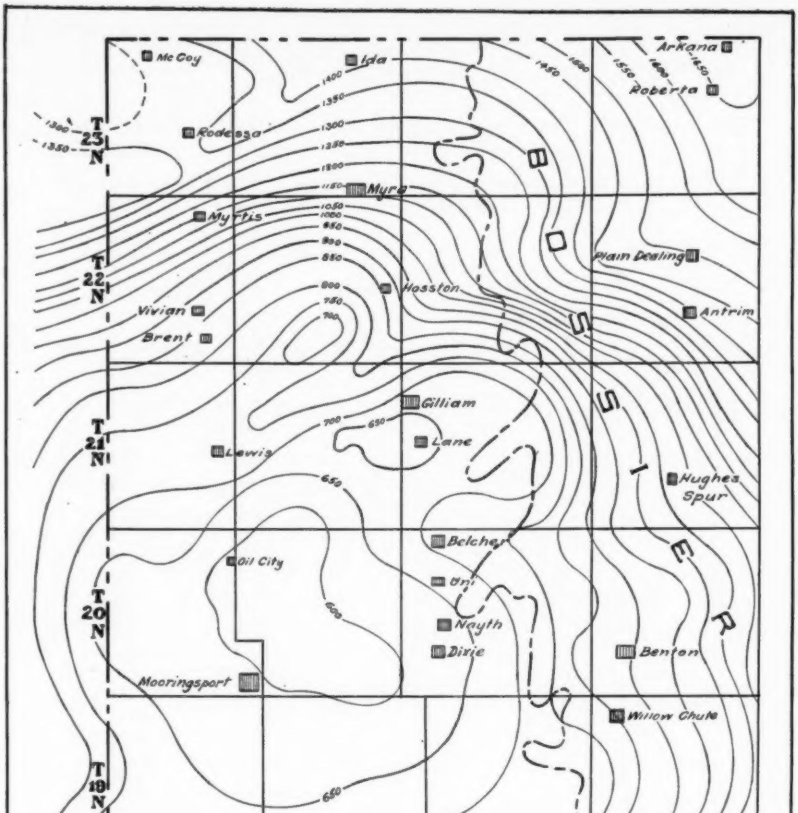

T 23 N
T 22 N
T 21 N
T 20 N
T 19 N
T 18 N
T 17 N
B O S S I E R
C A D D O
R16W
R15W
R14W
R13W
LOCATION OF OIL AND GAS PRODUCTION
Scale of Miles:
LEGEND:
OIL
GAS
Wm M. Barret
Shreveport, La

FIG. 1



Mc Coy
Ida
Arkana
Roberta
Rodessa
Myra
Myrtis
Plain Dealing
Hosston
Antrim
Vivian
Brent
Gilliam
Lane
Lewis
Hughes Spur
Belcher
Oil City
Uni
Nayth
Dixie
Benton
Mooringsport
Willow Chute
Vanceville
Blanchard
Brownell
Longwood
Shreveport
Waskom
Greenwood
B O S S I E R
C A D D O
T 23 N
T 22 N
T 21 N
T 20 N
T 19 N
T 18 N
T 17 N
R16W
R15W
R14W
R13W
CONTOURS ON TOP OF PRODUCING SAND IN NACATOCH FORMATION. INTERVAL 50 FEET
Scale of Miles:
Wm. M. Barret
Shreveport, La.

FIG. 2

shows that the dip occurs at a comparatively rapid rate on the north, east, and west flanks of the uplift. Toward the south the beds dip at a much more moderate rate, terminating in a structural basin fairly centrally located on the Sabine uplift.

MAGNETIC CHARACTERISTICS

Before considering a detailed magnetic study of the uplift it will be well to refer briefly to the regional distribution of the vertical field. The boundary of the Sabine uplift conforms very closely with a closed magnetic "high" of approximately 100 gammas. As the Caddo-Shreveport uplift is located on the northern end of the Sabine uplift it is evident that the area is magnetically positive in a regional sense.

Figure 3 is a vertical intensity-contoured chart showing the variation of the vertical element throughout the area covered by the structural details of Figure 2. A latitude and longitude correction of 15 gammas per mile and 3 gammas per mile, respectively, has been applied to compensate for the normal change of the vertical field. In order to present clearly the effect of polarization of the uplift the average vertical intensity throughout the general area is represented by the line of zero anomaly, the positive and negative variations from this reference line being indicated at intervals of 25 gammas.

The salient features indicated by Figure 3 are a magnetic "high" of 225 gammas, centering on Sec. 1, T. 18 N., R. 15 W., with a corresponding magnetic "low" of 225 gammas, centering on Sec. 33, T. 22 N., R. 15 W., the magnetic axis connecting these disturbances being inclined at an angle of 13° west of true north.

In every case involving geomagnetic investigations of producing fields it is necessary to consider the probable distortion of the magnetic elements due to the presence of well casing, tubing, et cetera. Some investigators have contended that the association of pronounced magnetic "highs" with certain producing fields have been due, largely, to the presence of this metal. In the writer's opinion the opposite effect is to be expected, as the concentration of the vertical lines of force in the highly permeable casing causes a corresponding decrease in field strength in the region surrounding the metal. The principal doubt seems to arise in regard to the probable spatial distribution of this weakening effect. Errors from this source can be minimized by a judicious selection of the station locations.

Before considering the correlation of the magnetic and geologic data let us briefly review the possible warping effect of the vertical

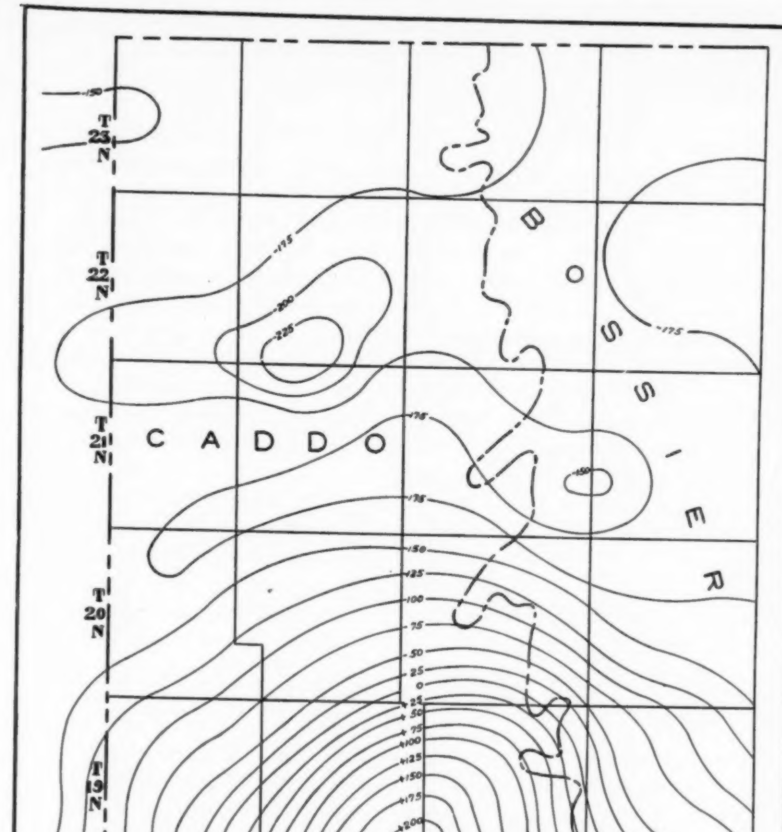

BOSSIER
CADDO
T 23 N
T 22 N
T 21 N
T 20 N
T 19 N
T 18 N
T 17 N
R16W
R15W
R14W
R13W
VERTICAL INTENSITY MAGNETIC CHART CORRECTED FOR REGIONAL VARIATION
Scale of Miles:
Interval 25 Gammas
Wm. M. Barret
Shreveport, La.

FIG. 3

element by the local influences previously mentioned. Little drilling has been done in the area of the magnetic "high" proper; consequently, there is little reason to suppose that this feature has suffered distortion from stray magnetic fields originating in the well casing. If we consider the magnetic "low" indicated on Figure 3 as intimately correlated with the presence of the casing, it is justifiable to suppose that the center of the negative disturbance should be fairly symmetrical with respect to the center of the producing area of the Caddo field. An examination of Figures 1 and 3 shows that this is not the case, because their centers are displaced a distance of approximately 5 miles. As further proof that this magnetic "low" is primarily due to geologic conditions rather than local interference, it is observed that the magnetic gradient rises very slowly in three directions from this area of magnetic depression, which is contrary to what might be expected if we considered local influences responsible for the effect. That the lines of force delineating the magnetic field, as illustrated in Figure 3, have been warped from their symmetrical paths, by virtue of the thousands of tons of metal associated with the producing regions, is doubtless true. However, it is confidently believed that what aberration, from this source, exists will not obscure the geomagnetic treatment of the structure.

The involved nature of the problem of translating the anomalies is readily understood when it is realized that several disturbing features are responsible for the complex resultant field at the surface. Let us analyze the various factors contributing to this resultant field. Of first importance may be mentioned the normal field of the earth. The introduction of the Sabine uplift produces a deformation of this original field, and the superimposition of the Caddo-Shreveport uplift on the Sabine uplift causes a further distortion. It is indeed surprising that the areal pattern of the resultant anomalies is as symmetrically arranged as indicated in Figure 3.

Definite conclusions regarding the anomalies directly associated with the Caddo-Shreveport uplift would, of necessity, presuppose a thorough understanding of the anomalies assignable to the normal earth's field as well as those arising from the Sabine uplift. Unfortunately, the information available at present yields only superficial data on these disturbances.

To correlate the resultant anomalies several hypotheses are tenable. First, we may assume that the basement rocks, together with the Lower and Upper Cretaceous composing the major and minor anticlinal features, have coördinated in producing the pronounced positive disturb-

ance of Figure 3. A major magnetic distortion would be anticipated from a basement of granite or Pennsylvanian formations and the beds, rich in hematite and pyrite, which overlie the basement. To be in symmetrical relationship with the Sabine uplift, the center of this distorted area would lie on the prolongation of the magnetic axis, approximately 18 miles south of the magnetic "high" pictured in Figure 3. This shift could be explained by a consideration of the inclination of the lines of force of the earth's magnetic field together with a spatial deformation produced by the relatively shallow beds of the minor uplift. In further support of this theory the reader's attention is called to the sharp decline of the magnetic gradient between the principal disturbances of Figure 3. A southward displacement, along the magnetic axis, of the positive disturbance would result in a more uniform areal distribution of the lines of force. It is known that the attitude of tabular forms has a pronounced effect on the influence they exert in distorting the earth's field. The rapid dip of the formations on the north boundary of the Caddo-Shreveport uplift, in which region the edges of the major and minor uplifts practically coincide, might account for the localized negative feature of Figure 3.

Adopting another theory to explain the pattern of the anomalies, we might attribute the disturbances of Figure 3 entirely to the minor anticline, the deeper-seated reactions having been masked by the younger geological section containing concentrations of ferromagnetic and paramagnetic minerals. The relations of the magnetic and structural profiles, corresponding with the Caddo-Shreveport uplift, are shown in Figure 4. These profiles have been drawn along the magnetic axis, the curve representing the geologic structure being greatly exaggerated to facilitate comparison. This latter curve indicates the rapid dip of the formations on the north end of the uplift. Continuing along the magnetic axis, toward the south, the beds present a monoclinal feature, the Nacatoch formation dipping to a depth of $-1,000$ feet at approximately 12 miles from T. 17 N., at which point the magnetic profile has dropped to -35.

It is observed that a marked similarity exists between the profiles of Figure 4. The irregularities appearing between Townships 21 and 22, as well as the fact that the intersection of the magnetic profile and the line of zero anomaly is in vertical relationship with that part of the geologic profile representing greatest structural relief, accord with the inference that the major anomalies are traceable to the dominant distortion of the Caddo-Shreveport uplift. At this point the writer directs attention to the analogy existing between these profiles and those relating to gravi-

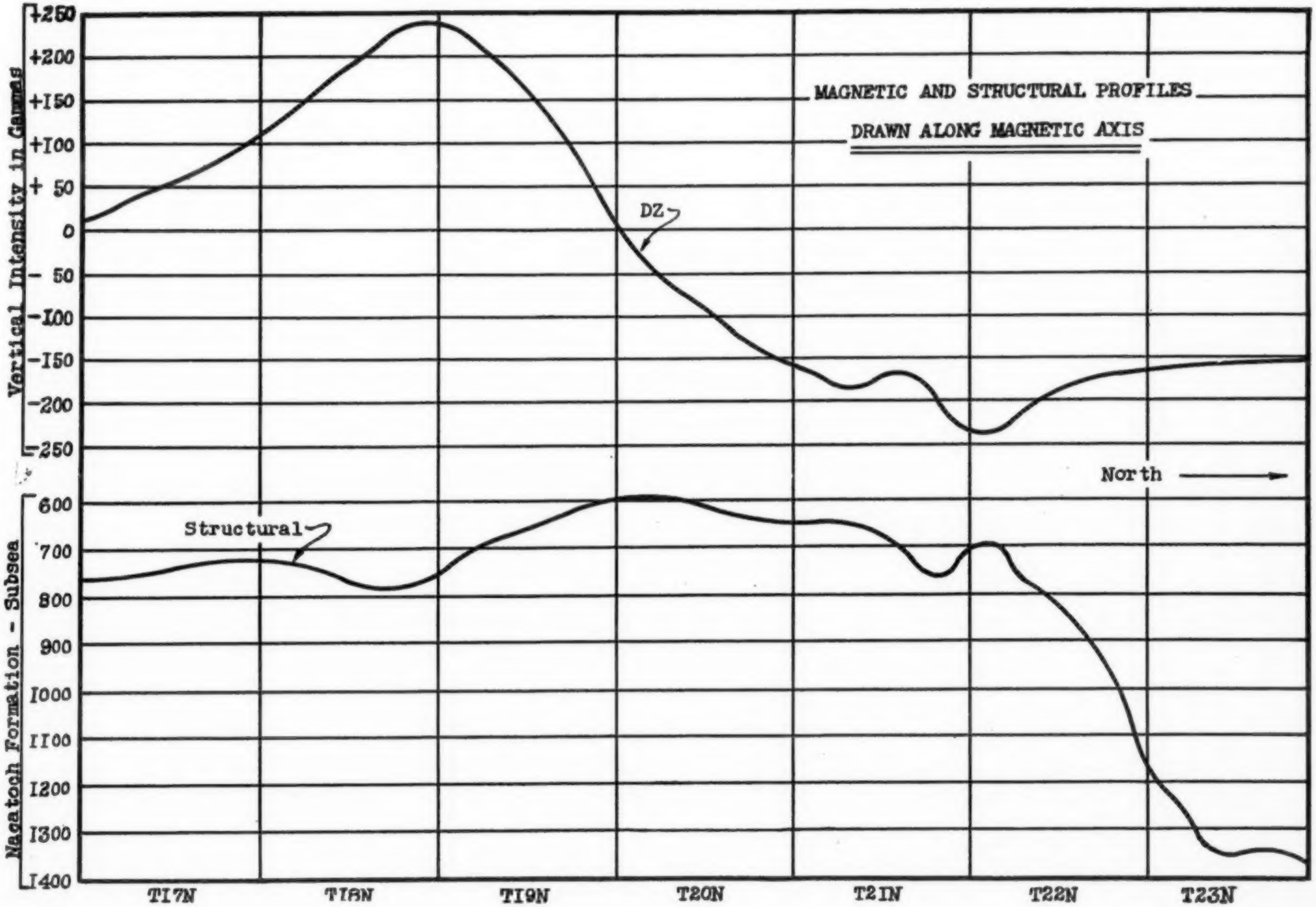

MAGNETIC AND STRUCTURAL PROFILES
DRAWN ALONG MAGNETIC AXIS
Vertical Intensity in Gammas
+250
+200
+150
+100
+ 50
0
- 50
-100
-150
-200
-250
DZ
North
Structural
Nagatoch Formation - Subsea
600
700
800
900
1000
1100
1200
1300
1400
T17N
T18N
T19N
T20N
T21N
T22N
T23N

FIG. 4

tational measurements. Over the geologic section shown, the magnetic profile would bear a striking relation to the gravity gradient in torsion-balance work, which is significant in the light of Albert Einstein's recently established identity. Continuing, the reader is referred to Figure 3, in which the intersection of the line of zero anomaly and the magnetic axis falls over the approximate center of the uplift, and further, the inclination of the magnetic axis conforms closely with that of the structural axis.

The localized regions of north and south polarity may be ascribed to differential permeability or to induced polarization of the tabular mass, the latter interpretation being supported by empirical data collected from surveys of somewhat similar, isolated, geologic disturbances occurring in the same general geographic region as the uplift. These data evidence, in some instances, the same linear displacement of the magnetic profile, with respect to structure, as that demonstrated by Figure 4. The resemblance of these corroborative profiles to the present interpretation seems to indicate that the major anomalies can not be attributed to the presence of media of differing magnetic permeabilities.

As a plausible explanation of the apparent polarization we may suppose that the north polarity of the magnetic profile, shown between T. 21 N. and T. 22 N., is produced by the nearer approach to parallelism, with the earth's resultant field, of the plunging tabular forms on the north end of the uplift; and that the south polarity, indicated between T. 18 N. and T. 19 N., is a result of the dominant field of the uplift proper, shifted somewhat south of the symmetrical center of the uplift by the warping effect of the deeper formations.

Only a general interpretation can be drawn until more is known concerning the anomalies associated with the deep-seated bodies, and until we have a more intelligent understanding of the distribution of the ferromagnetic, paramagnetic, and diamagnetic minerals within the rock masses involved.

WAVE-FRONT DIAGRAMS IN SEISMIC INTERPRETATION[1]

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ABSTRACT

Subsurface structure can be derived from seismic data by graphical methods based upon wave-front diagrams. The method of construction of these diagrams is shown, and the nature and origin of the important underlayer wave is explained. Coincident-time curves and secondary shotpoints are defined and some applications are illustrated. The diagrams are used to explain some of the simpler seismic rules, and the original determination of simple underlayer structure is illustrated. The paper is only an introduction to wave-front methods; the principles developed can be applied by experienced seismologists to more complex situations.

INTRODUCTION

It is not generally known that practically every problem to which seismic methods can be successfully applied can be solved in whole or in large part by graphical methods, entirely devoid of formulae. Such methods should appeal to geologists, because of the high interpretative value of the diagrams involved and because of the lack of mathematics. Graphical depth construction methods have been published by Schweydar, Meisser, and others, but the writer has seen nothing in the literature descriptive of this method or its principles, which are quite different and more generally applicable.

The basis of this method is the wave-front diagram. This paper is presented in an effort to introduce such diagrams, particularly to geologists. It is not intended to be a complete exposition of wave-front graphical methods. Only a few simple situations have been considered with a view to illustrating the principles involved. There are many applications in which these principles can be used.

Interpretation is the most advanced and difficult part of commercial seismology. It is closely interwoven with field work, and for this reason should not be attempted by one unfamiliar with the conditions (instrumental and otherwise) under which the field work was performed. It is naturally left in technical hands. Nevertheless, all such work is

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directed by geologists, who should therefore certainly be familiar with its broader principles. Practically all of the field seismologists of the writer's acquaintance would gladly welcome an increased knowledge of the simpler cases of interpretation on the part of the geologists under whom their work is done. Wave-front diagrams are recommended for this purpose. Although slow and tedious to construct, they are simple and easy to understand. They should pay a fair dividend of comprehension on the invested time and patience. If the geologist will take the trouble personally to construct and study diagrams such as those of Figures 4 and 5 of this paper, he will learn several things of interest concerning time-distance curves and seismology in general.

Wave-front diagrams provide a unique method of visualizing, both qualitatively and quantitatively, what occurs underground when a charge of explosive is fired at the surface. They are of use in explaining some of the simplest of seismic phenomena. They can be used to verify the conclusions reached by other methods in highly complicated cases. They are of particular value in checking assumed profiles and structures against the original data. Geophysicists who have confined their interpretations to equations will find that the principles here outlined can be used to good advantage. Advanced methods based upon wave-front diagrams can be used in a direct method in which the most probable geologic structure is derived from the observed data. In such cases a complete picture of the geologic section is built up, step by step, from the surface downward. If carefully applied, the method can be used on fan-shooting to great advantage. The wave-front diagram not only shows *all* ray paths, but also *time* relationships; which ray diagrams do not. It also helps to visualize the volume-distribution of energy; thus, it is an aid in studying field records.

The first reference to wave-front diagrams known to the writer was made by Merten of the Shell organization late in 1927. Here "a system of rays and isotime curves" was used in a series of graphical approximations to obtain the correct profile of a Louisiana salt dome. His isotime curves are the wave-fronts of this paper. His rather fragmentary conception of wave-front diagrams was rapidly amplified. A report by Merten (January, 1928) contained a figure essentially like Figure 1, except for the coincident-time curves, which are the writer's conception.

Acknowledgments are due to F. H. Lahee and D. C. Barton, for helpful criticisms and suggestions during the preparation of this paper.

DIAGRAM CONSTRUCTION

DEFINITIONS

A wave-front is defined as the surface passing through the most advanced positions reached by a specified disturbance at any particular time. It changes its position with time. In this paper the term is used in a restricted sense to designate the curve formed by the intersection of the wave-front surface with any particular plane or section in which we may be interested.

A "wave-front diagram" is therefore defined as a composite figure, showing the intersections of the various wave-fronts with a specified plane at successively equal time intervals.

DEVELOPMENT OF DIAGRAM

Figure 1 shows such a wave-front diagram for an idealized geologic section, consisting of a surface formation and two underlying flat formations. The constants used in the construction of the figure are:

Formation	*Thickness (Feet)*	*Speed (Feet per Second)*
Surface	2,000	5,000
First underlayer	4,000	7,500
Second underlayer		10,000

Notice in passing that we assume: (1) underlayer tops to coincide with formation boundaries, (2) positively nothing concerning the character of the disturbance except its speed of transmission, and (3) the transmission speed to be constant throughout each separate underlayer.

The entire construction is based on Huygen's principle: each point on a wave-front may be considered as a source for new waves. The time interval chosen for Figure 1 is 0.1 second. During this time the disturbance travels 500 feet in the surface formation, 750 feet in the first underlayer, and 1,000 feet in the second underlayer. These, therefore, are the least distances between any two adjacent wave-fronts, provided they are measured in one formation only. Where a wave crosses a boundary in this time interval, its progress can be traced by a supplementary construction in which a shorter time interval (0.01 second) is used.

In Figure 1, *S* is the shotpoint from which the disturbance radiates with the speed indicated. The concentric curves represent successive positions of the wave-front with the 0.1 second time interval. It is easy to see how the disturbance spreads with a circular front while in the surface formation. It is not difficult to see how the change in velocity of

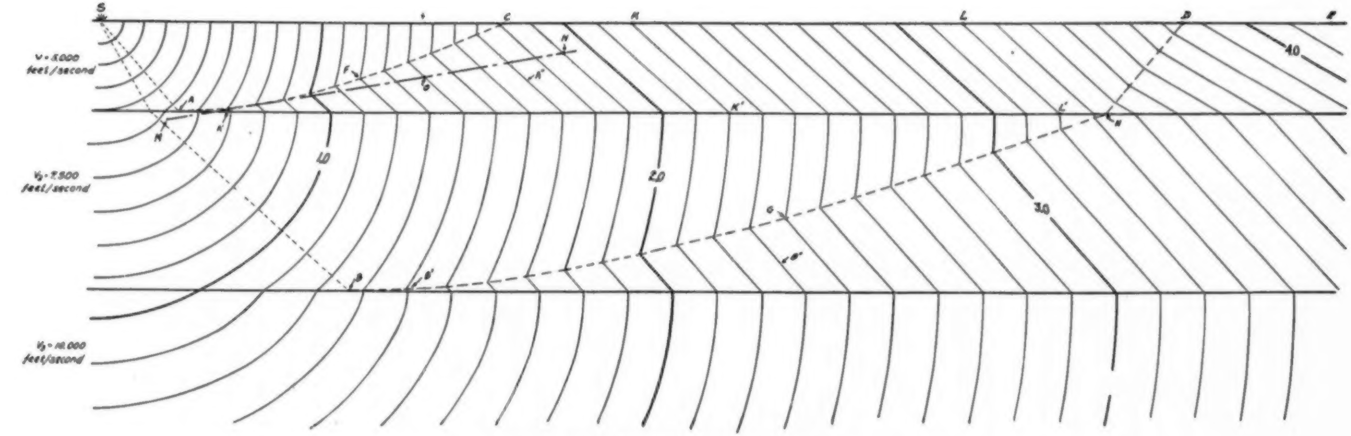

FIG. 1.—First impetus wave-front diagram.

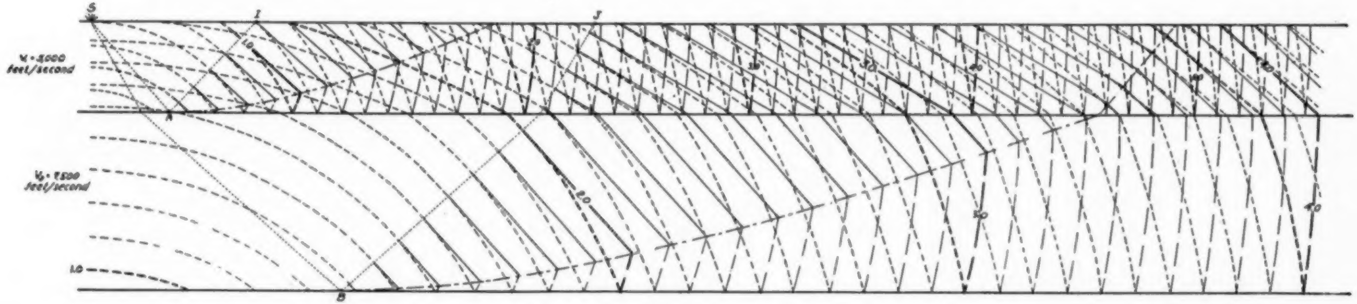

FIG. 2.—Wave-front diagram for late impetuses.

the disturbance, in passing a boundary, distorts the front out of circular form in the new medium. These are simple refraction phenomena, easily understood from elementary physics and optics.

Inasmuch as a wave travels at right angles to its front, Figure 1 shows a part of the original disturbance refracted at A so that it travels in and along the top of the first underlayer as if it originated at A. It also shows a similar type of disturbance travelling in and along the top of the second underlayer as if it originated at B. A and B are points at which total reflection (of a disturbance originating at S) would occur in optics.

Consider the points beyond A on the boundary between the surface and the first underlayer. Because of the location of A, and because of the higher speed of the underlayer, these points are first reached and set in motion, not by the direct wave from S, but by the disturbance travelling in and along the top of the underlayer. Their motion disturbs the adjacent points in the surface formation which are so far at rest; so that some sort of disturbance wave is generated and radiated back into the surface formation. This "underlayer wave" has a straight-line wave-front. It begins to develop at A, is first apparent at A', and is well developed at A''. In a similar manner the second underlayer wave begins to develop at B, is first apparent at B', and is well developed at B''.

To assist in visualizing the nature and origin of this straight-line underlayer wave-front a simple analogy follows. Observe a stick being dragged through the water along the shore of a lake, with a velocity greater than that of a free surface wave in water. It will be noticed that the wave-front of the ensuing disturbance on the surface of the water is a straight line with origin at the stick, and that its angle with the shore is successively smaller the greater the velocity of the stick. In this analogy the disturbance caused by the stick corresponds with the disturbance travelling along the top of the underlayer from A, and the shore of the lake corresponds with the formation boundary. The water corresponds with the surface formation, and the wave-front generated in it corresponds with the straight-line wave-front radiated back into the surface formation. The greater the difference in velocity between the two formations the smaller the angle between the formation boundary and the "underlayer wave."

This underlayer wave is the phenomenon which makes possible the use of seismology as an aid to geology. The important thing about it is that the angle it makes with the boundary at which it originates is

entirely independent of the position of the shotpoint, formation thickness, and everything else except the velocity ratio of the two formations adjoining the boundary.

If the first underlayer had a velocity lower than that of the surface formation, the circularly spreading disturbance front in the surface formation would be simply refracted downward into the first underlayer, and no "underlayer wave" would be generated. This is important, because it tells us that only those boundaries at which the velocity increases with depth will generate underlayer waves. Its application to geology is obvious.

Figure 1 shows only the most advanced positions of the original disturbance at any specified time. These disturbance fronts are not simple wave-fronts, but are a composite of several wave-fronts of different origin and history. For example, the 2.0-second front of Figure 1 consists of four different simple wave-fronts. The part in the surface formation is the "first underlayer wave." The part between the top of the first underlayer and the curve *BGH* is the refracted wave travelling through the body of the first underlayer. The remaining part in the first underlayer is the "second underlayer wave." The part in the second underlayer is the refracted wave travelling through the body of that underlayer. Merten sought to emphasize the composite character of the disturbance front by calling it an "isotime curve."

The disturbance fronts shown in Figure 1 are not the only real ones. At any point between *C* and *D* on the surface, the ground is first disturbed by the first underlayer wave. Nearer to *S* the ground is first disturbed by the direct wave from *S*. Beyond *D* the first disturbance is produced by the second underlayer wave. But over this entire interval all three waves are real and ultimately disturb the surface of the ground.

Figure 2 is the same geologic section, showing the remaining possible real wave-fronts which travel with the velocities noted. The disturbance fronts of this figure are those which travel as a second or later impetus. In addition to the reflections, which are never first impetuses, the figure shows the later parts of the waves of the first diagram. The two figures rightly belong on a single diagram, but are shown separately for the sake of greater clarity.

COINCIDENT-TIME CURVES

Consider the curves *AFC* and *BGHD* of Figure 1. Curves such as these are formed wherever two different wave-front systems intersect each other. They are important in interpretative work, both

graphical and otherwise. Together with the formation boundaries these curves mark off the section into zones. Each zone contains all of the wave-fronts of a specified system which travel as a specified impetus. By construction, any point on such a curve is equally time-distant from the shotpoint along two different paths. For this reason the writer here proposes the name "coincident-time curves" for such lines.

Coincident-time curves for the surface-first underlayer wave systems are parabolas, because each point on them is equally distant from a point and a line. For the other underlayer wave systems, the coincident-time curves depart slightly from a parabola, inasmuch as one set of waves is no longer strictly circular.

Coincident-time curves are worthy of study. Wherever they intersect the ground surface, there is a "nick" or "break" in the time-distance curve. At such points there is a change from one set of waves to another. This change is abrupt; the time-distance curve is discontinuous at such points. Wave-fronts of a single system are not discontinuous, so that their time-distance relation from the shotpoint is plotted, without exception, as a smooth graph, without discontinuities. The presence of such breaks on the graph is therefore a signal that a change is taking place from one set of waves to another. Unfortunately, in practice it may not be possible to secure data sufficiently precise to determine positively the presence of such a break.

Interpretation of structure is closely connected with these coincident-time curves. In depth they are tangent to underlayer tops. If the underlayers are flat, these curves "crop out" at the same distance from the shotpoint in all directions. The deeper the beds, the farther away from the shotpoint is this break. For a single underlayer the direction in which this break is closest to the shotpoint is the direction in which the underlayer has a maximum rise, that is, its "up-dip" direction; and so on.

SECONDARY SHOTPOINTS

As already noted, the points *A* and *B* of Figure 1 act in some ways as new point sources for disturbances. In salt-dome work, points common to the dome and two underlayers may act in this manner also. Such points, at least theoretically, give rise to new wave systems; therefore, to new coincident-time curves. These curves, in turn, may be of considerable value in interpretation. For such points the writer proposes the name "secondary shotpoints." The terms "secondary foci" or "secondary origins" would be more in conformity with scientific seis-

mological terminology, but the term here proposed is believed to be of greater descriptive value as applied to commercial practice.

TIME-DISTANCE CURVES

No matter how complicated or involved the field procedure of the seismologist may be, the quantities of most importance to him, and the only quantities which can be observed directly, are time and distance; time between the instant of explosion of a charge at the shotpoint and the arrival of the resulting disturbance at the instrument point, and distance between shot and instrument points. These two quantities are observed for a number of instrument points and the data are summarized into a "time-distance" curve, which shows at a glance the variation of travel-time with shotpoint distance. Interpretation is roughly the process by which the most probable geologic subsurface structure is derived from these curves.

If we summarize the data of Figure 1 in such a manner, we secure the graph of Figure 3. Here the distance from *S* of each particular wave-front intersection with the ground surface is plotted against the time of that wave-front. The broken line *SCDE* is the result. It alone is what would be referred to in practice as the time-distance curve for the geologic section. By like measurements of Figure 2, we complete Figure 3, as shown.

SIMPLE APPLICATIONS OF WAVE-FRONT DIAGRAM

FIRST SURFACE APPEARANCE OF UNDERLAYER WAVE

At a surface point in the vicinity of *C* (Fig. 1), but nearer *S*, we know that the first underlayer wave is real, but later than the direct surface wave. In the vicinity of *S* there is no real first underlayer wave, so that it must make its initial surface appearance somewhere between these two points. If we study the reflected and underlayer waves produced by the first underlayer in Figure 2, we see that in the region toward *S* from the ray *AI* there is no such wave present. This wave-front is tangent to the reflected wave-front along this ray *AI;* but though the reflected wave is real on both sides of the ray, the underlayer wave does not exist on the shotpoint side. Stated differently, the underlayer wave becomes a true reflection if we approach the shotpoint close enough. In Figure 3, we can say that the first underlayer line does not extend to the left of *I*, and the second underlayer line does not extend to the left of *J*. At these points these lines are tangent to the corresponding reflection curves.

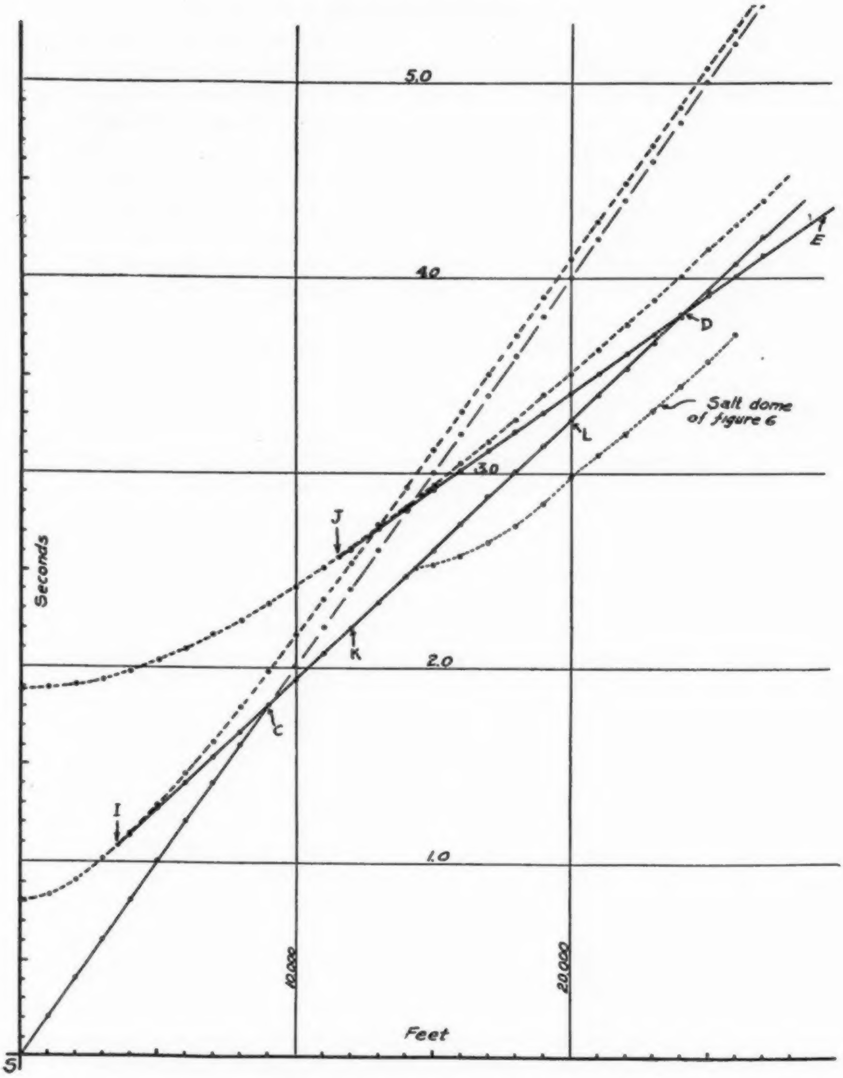

FIG. 3.—Time-distance curve for Figures 1, 2, and 6.

APPARENT VELOCITIES

Consider Figure 1 and its corresponding time-distance graph in Figure 3. The points *S* and *C* are separated by a time and by a distance. Their ratio gives a velocity, which turns out to be the true velocity of the surface formation. *K* and *L* are two points on the first underlayer line. An apparent velocity determined from these points is quite different from the surface velocity. Referred to Figure 1, at first sight it does not appear to have a real meaning, because it is a surface distance divided by a time interval between two wave-fronts which strike the surface obliquely. But if *KL* is slid down along the wave-fronts it will coincide with *K'L'*, because the top of the first underlayer is parallel with the ground surface. It is now the perpendicular distance between the wave-fronts; therefore, the velocity obtained from it is the true velocity of the disturbance in the underlayer. By use of the same method it can be shown that the apparent velocity derived from the points *D* and *E* is the true velocity of the corresponding underlayer. We can summarize this into the rule: where beds are flat and the ground surface is level, apparent velocities as shown by the inclination of the underlayer lines on the time-distance curve are true velocities of the corresponding underlayers.

With a wave-front diagram it is easy to show the effect on apparent velocity of inclined beds. This is done in Figure 1 by imagining the surface line tilted. If the first underlayer dips toward the shotpoint, the distance *KL* will be greater than *K'L'*, so that the apparent velocity will be greater than the true velocity (greater distance divided by the same time). If the underlayer dips away from the shotpoint the apparent velocity will be less than the true velocity, inasmuch as *KL* will be smaller than *K'L'*.

A little study will show that a specified distance between two underlayer wave-fronts where they intersect the surface can not be made to fit horizontally between the same two wave-fronts where they intersect the top of their horizontal deeper underlayer unless the tops of all intervening underlayers are also horizontal. Stated differently, this means that the apparent velocity derived from the time-distance curve for a horizontal deeper underlayer is not the true velocity unless all intervening underlayers are also horizontal.

RELATIONSHIP BETWEEN VELOCITY, DIP, AND DEPTH

For each particular wave-front system in a surface formation there is a particular time-distance curve. It is therefore of considerable im-

portance to know if it is possible for two different geologic sections to produce identical surface formation wave-front systems. Consider this pattern for the left half of Figure 1, consisting of the circular surface waves, the straight-line first underlayer waves, and the coincident-time curve AFC. This curve is tangent to the first underlayer at A. If the top of this first underlayer had the position MN (still tangent to the coincident time curve), and had a different velocity (equal to the distance ON divided by the corresponding time interval), it would still produce the same surface formation wave-front systems. From this we can see that there is a relationship between underlayer velocity, dip, and depth under shotpoint; but by a suitable choice of these three quantities there is an infinite number of first underlayers which will produce the same time-distance curve at a single shotpoint. Unless we know one of these three quantities there is no unique solution to our problem.

These considerations demonstrate that a single lineshot is insufficient positively to determine subsurface structure. This does not mean that we can not draw fairly dependable conclusions concerning it by making certain probable assumptions. But we must not forget that the conclusions are based on assumptions. For example, if we assume a true velocity (from previous shooting in that general area) we can solve for the underlayer of the preceding paragraph. If we assume the underlayers to have constant velocities throughout the area being worked, it follows that, if the underlayer lines on the time-distance graph are curved, the underlayers themselves are curved, and so on.

ORIGINAL DETERMINATIONS

So far we have considered only the construction of the diagrams and their use in deriving some of the simplest of seismic rules. We now outline the fundamental application of wave-front diagrams in the determination of structure directly from original data.

All waves, no matter what their path or where they originate, can travel only with surface velocity while in the surface formation. If we know this velocity, we can always reconstruct, for a specified time-distance curve, the positions of the wave-fronts in the surface formation as these waves emerge at the surface. This is done by reversing the process by which Figure 3 was obtained. As we can not definitely determine structure by a single lineshot, we will "reverse shoot" the area, so that we have two time-distance curves over the profile in opposite directions. We will assume that on plotting the data we obtain the curves of Figure 4. Simple inspection shows that the surface velocity

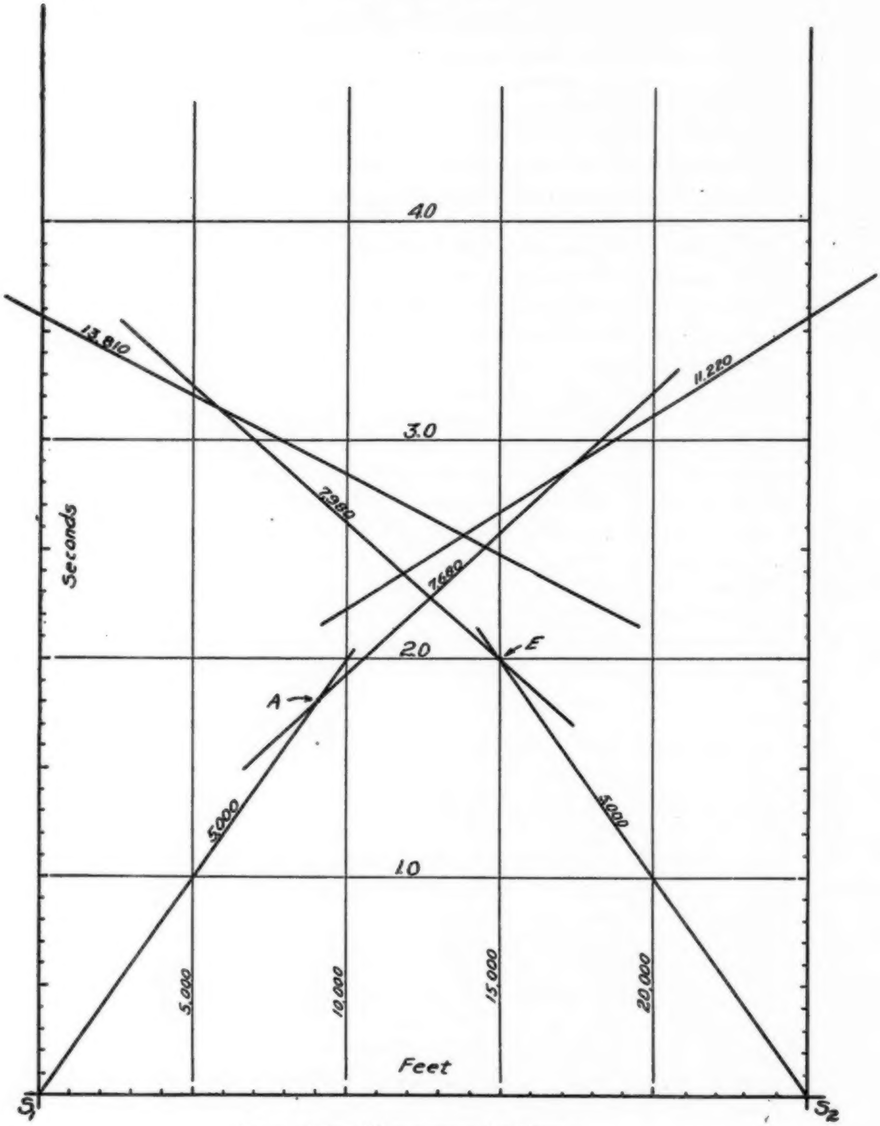

FIG. 4.—Time-distance curves for Figure 5.

is constant; that there are two underlayers; that their upper boundaries are plane surfaces; and that both are inclined and dip toward shotpoint S_2.

In Figure 5, construction is started by laying off the surface line and plotting the shotpoint locations at the proper distance interval. The direct circular surface wave-front systems are next drawn for each shotpoint. The construction of the first underlayer wave-front system in the surface formation follows. This is done by selecting any point (A, Fig. 4) on the first underlayer line which will be on one of the wave-fronts. (In the figure, the point A happens to coincide with the surface-first underlayer break, but this is not at all necessary. The points A and E can be chosen at random anywhere along the first underlayer lines.) The wave-front AB (Fig. 5) is drawn in, care being taken that the angle it makes with the ground surface satisfies apparent first underlayer and true surface velocities. Earlier positions of the wave-front are drawn. The coincident time curve ACD for these two wave-front systems can then be drawn in by matching wave-fronts of corresponding time.

The same procedure is followed for shotpoint S_2. The circular surface waves are drawn, a point such as E on the first underlayer line is selected, and the wave-front EF is constructed; it must be borne in mind that the underlayer apparent velocity is different for this shotpoint. Wave-fronts are matched, and the coincident-time curve EGH is drawn.

Since the underlayer has a flat top, we can draw in this boundary as a straight line tangent to the two coincident-time curves ACD and EGH. From the intersection of the underlayer waves with this line we can determine the true velocity of the underlayer. We have a rigid check, in that the velocity must be the same for each shotpoint determination.

Knowing the position of the first underlayer, and having determined its velocity, we can construct the refracted wave-front system in this underlayer by the method of Figure 1, working from the shotpoints. The next step is to construct, in the surface formation, the wave-front system of the second underlayer wave. The method of obtaining the position and angle of one of the wave-front lines is the same as that used for the first underlayer. This line is then worked backward into the first underlayer and new coincident-time curves found for the second underlayer. These two coincident-time curves, one for each shotpoint, determine the position and velocity of the second underlayer. The

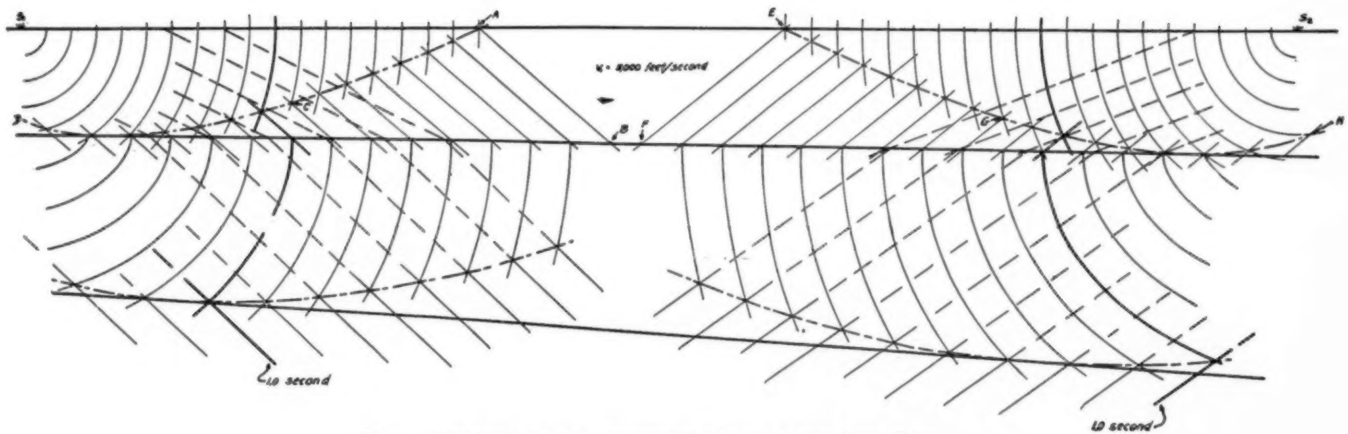

FIG. 5.—Graphical underlayer construction by use of wave-front diagrams.

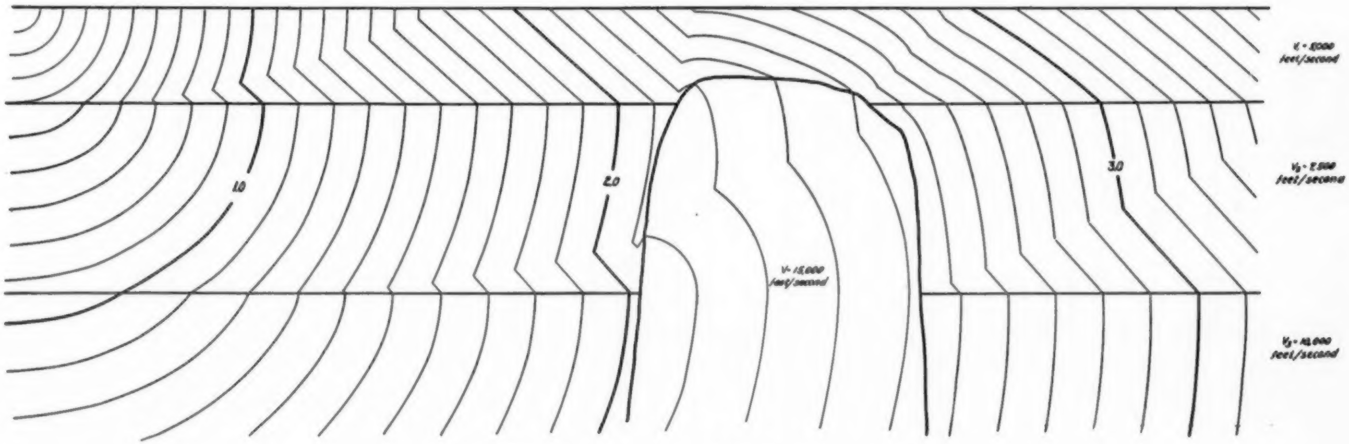

FIG. 6.—Wave-front diagram for idealized salt-dome profile.

check velocity should always be applied. The general method can be continued for deeper underlayers.

Figure 5 should illustrate that it is not essential for the lineshot S_2 to be made toward S_1. It could be made in the opposite direction, still in the vertical plane of the two shotpoints. Or we could make the two lineshots mutually perpendicular, and by a careful checking of real velocities out from each shotpoint, determine the underlayer attitude in two directions at right angles to each other. Other possibilities will be suggested by a study of the figure.

APPLICATION TO SALT-DOME WORK

Wave-front diagrams are particularly applicable to detail work for profiles containing large irregular subsurface masses such as faults or salt domes. In such complicated situations, the general principle used with Figure 5, together with other graphical principles not mentioned here, can be used on original determinations if the field data are clear, and with better success than by the use of mathematical formulae alone. They are also particularly applicable to the checking of final profiles against original field data. In such cases any draftsman familiar with the general principles of wave-front diagram construction outlined here can perform this checking. Figure 6 is an example of the application of the general method in such situations. It shows an idealized salt-dome profile—ideal because the underlayers are not disturbed by the dome presence and because the dome has no cap. This situation would probably never occur in practice, but it illustrates the principles involved, and may be of interest.

CONCLUSION

Graphical methods emphasize the impossibility of interpreting deeper structure unless the overlying structure is known. This is an extremely important fact which should never be overlooked. Commercial investigations are of course based on the principle of maximum results for minimum expenditure. Under these conditions, in daily practice probably a majority of seismologists are forced to substitute probable assumptions in place of actual observational determinations. This is particularly true in regard to attitude and velocity of shallow formations, especially the surface formation. The continuous necessity for making assumptions tends to obscure their magnitude, and tends to foster an attitude on the part of the interpreter too far removed from that of scientific investigation. For this reason a periodical attempt to derive a complete geologic interpretation adequate to explain the ob-

served data is extremely valuable; the method here described will be found to emphasize in a most remarkable manner the nature of the assumptions on which a check is desired. Such procedure tends to establish a true balance between the accuracy of the observed data and the conclusions drawn therefrom, and tends to indicate the limits beyond which economy of operations should not be allowed to force field methods.

No edifice is more dependable than its foundations. The foundations of seismic work are field data. To obtain dependable instrument records and to interpret them correctly into a time-distance curve are more difficult than many realize. Due to general ground unrest, loss of amplitude, extraneous disturbance, or simply indifferent field procedure, impetuses are easily lost or incorrectly identified on the records. Such conditions may cause a time-distance curve appreciably removed from the truth. Such circumstances are the common ills which no method of interpretation can cure. What is claimed for this method is that the principle is sound, it is simple and so generally comprehensive that any problem capable of solution can be dealt with. To the writer's knowledge, this method has been applied successfully to detailed investigations of salt domes and has proved itself to the point where it can no longer be regarded as simply an interesting theory.

Experienced seismologists will no doubt raise the objections that the writer is giving away secrets, and that practically everything here demonstrated by wave-fronts could have been explained much more readily by elementary mathematics. The answer to the first is that in the writer's opinion seismology will decidedly benefit all around by open discussion. The second objection is largely true, but it is the writer's hope that this paper will serve as an introduction of the method to those not familiar with it. It should also illustrate to the geologist that it is possible to perform the "inner mysteries" entirely without mathematical formulae. It takes considerable judgment, experience, and training intelligently to apply formulae to complicated profiles. There is the ever-present danger of attempting to apply formulae which are not applicable, whereas the graphical method greatly reduces the risk by clearly indicating possible shorter time paths. Under such conditions the application of wave-front diagrams may not be much more complicated or involved than for the simple situations in which it is here applied.

A rule of good practical value is: if the field data are not sufficient for a wave-front solution, the problem can not be solved by any method.

GEOPHYSICAL PROSPECTING FOR OIL[1]

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ABSTRACT

Geophysical prospecting for petroleum strictly is an indirect method of mapping geologic structure. In it, three successive steps can be recognized in all of the methods: (1) the mapping of the areal variation of some physical effect at the surface; (2) the determination of the subsurface distribution of some physical property producing the surface effect; and (3) the interpretation of the geologic situation corresponding with the distribution of that physical property. The methods have their limitations through the incomplete concordance between structure and the distribution of those physical properties, lack of knowledge of the geophysical constants of formations, inexperience, and erroneous geologic information. There is a bare possibility of the direct determination of the presence of petroleum by the electric method. Although the positive value of geophysical methods has been demonstrated, they are no panacea for all the difficulties in prospecting for oil.

INTRODUCTION

The purpose of the writer is to draw an elementary picture of the geophysical methods of prospecting for petroleum, taken as a whole, rather than to give even an elementary technical understanding of any one of the several methods. It is designed for the layman in geophysics whether geologist, executive, technologist, or layman in science, and not for the student of geophysics. The purpose is to show how the geophysical methods of prospecting for petroleum indirectly, and more or less imperfectly, map geologic structure and allow the geologist then to make his guess in regard to the possibility of finding oil. The purpose is, also, to impress the fact that these geophysical methods of prospecting for petroleum are not infallible for finding structure and much less for finding oil, but that like the older methods of oil geology, they are an imperfect means of increasing the chances of success.

Geophysical prospecting for petroleum strictly is an indirect method of finding petroleum by indirect mapping of geologic structure. Three successive steps can be recognized in the operations of any of the methods: (1) the mapping of the areal variation of some physical effect at

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the surface; (2) the determination of the subsurface distribution of some physical property connected with the physical effect mapped; and (3) interpretation of the geologic structure probably corresponding with the distribution of these physical properties.

The geophysical methods of mapping in practical use are: gravitational, seismic, magnetic, electric, and electro-magnetic.

PHYSICAL EFFECTS MAPPED BY DIFFERENT METHODS

Three quantities: (1) the horizontal variation of the horizontal gradient of the intensity of gravity, that is, the rate at which the intensity of gravity increases horizontally, (2) the horizontal variation of the intensity of gravity, and (3) the differential curvature, which is a rather complicated function of the curvature of a level surface, are mapped with the Eötvös torsion balance.

The variation of the speed of transmission of elastic earth waves produced by artificial explosion, and to a less extent the variation of the character of the elastic earth wave are mapped by portable field seismographs.

The variation of the intensity of the earth's magnetic field, most commonly the intensity of the vertical component of the terrestrial magnetic field, is mapped most commonly with a Schmidt Lloyd magnetic variometer and to a less extent with dip needles or other types of instruments.

In the electric methods, which themselves form a rather composite group of methods, the surficial plans of electric fields and electro-magnetic fields are mapped. In some methods, the drop in current and the resistivity of the ground are mapped. In some, the plan of the equipotential lines, that is, the lines along which there is no flow of current, and in others the azimuth and dip of the electro-magnetic field set up by induction are mapped.

Characteristic maps of the variation of various physical effects at the surface are shown in Figure 1. The variation of the horizontal gradient of gravity around a salt dome is shown in Figure 1*A*. The variations of the speed of transmission of the elastic earth waves along a profile from a point above the salt of a salt dome to a point off the dome are shown in Figure 1*B*. The variations of the intensity of the horizontal (*H*) and the vertical (*Z*) components of the terrestrial magnetic field across the Panhandle buried granite ridge are shown in Figure 1*C*. A map of the lines of equal electric resistivity around the Hettenschlag salt dome in Alsace is shown in Figure 1*D*.

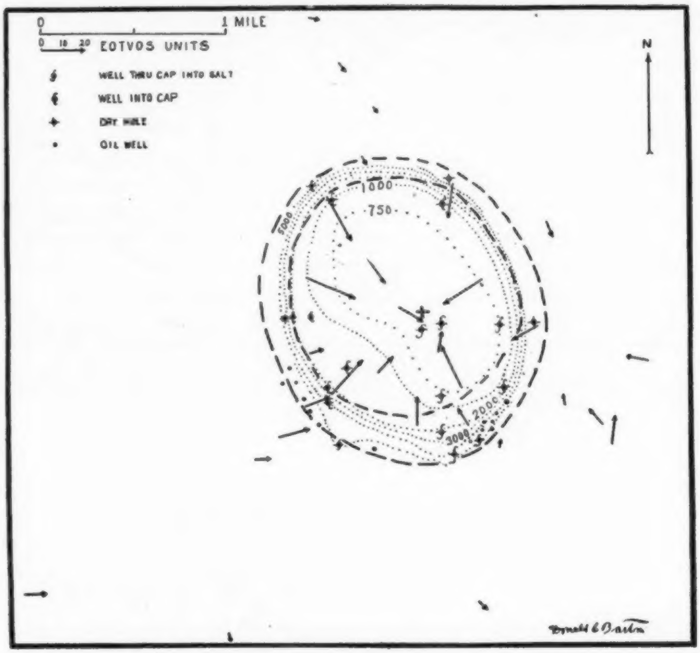


FIG. 1.—Surface variations of physical effects.

A. Torsion-balance method, gradient map of Nash salt dome. The length of each arrow represents the magnitude of the horizontal gradient of gravity and its direction gives the direction of the maximum gradient. The dashed lines show the predicted position of the salt at 500-900 feet and at 4,000-5,000 feet. The dotted contours are structure contours based on subsequent drilling. Survey by the Rycade Oil Corporation and the writer. Published by permission of the Rycade Oil Corporation.

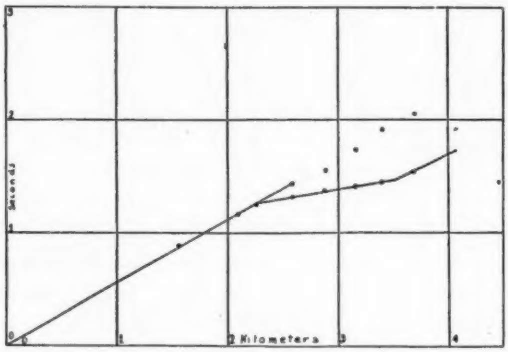


FIG. 1.—*B*. Seismic method, travel-time-distance graph from a point on a salt dome across the edge. From "The Eötvös Method of Mapping Geologic Structure," *Amer. Inst. Min. Met. Eng. Tech. Paper 50* (1928).

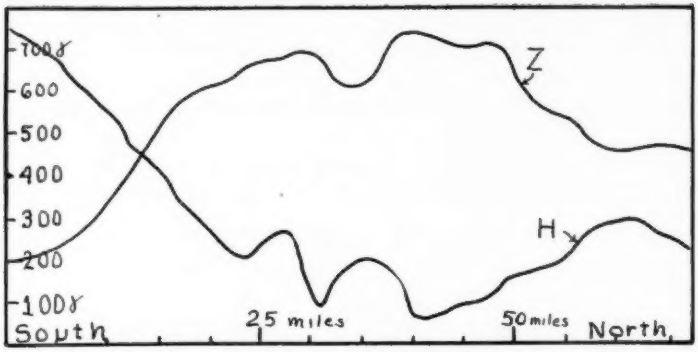


FIG. 1.—*C*. Magnetic method, profiles of the vertical (*Z*) and horizontal (*H*) components of terrestrial magnetism across the Amarillo (Texas) buried granite ridge. (After C. C. Adams)

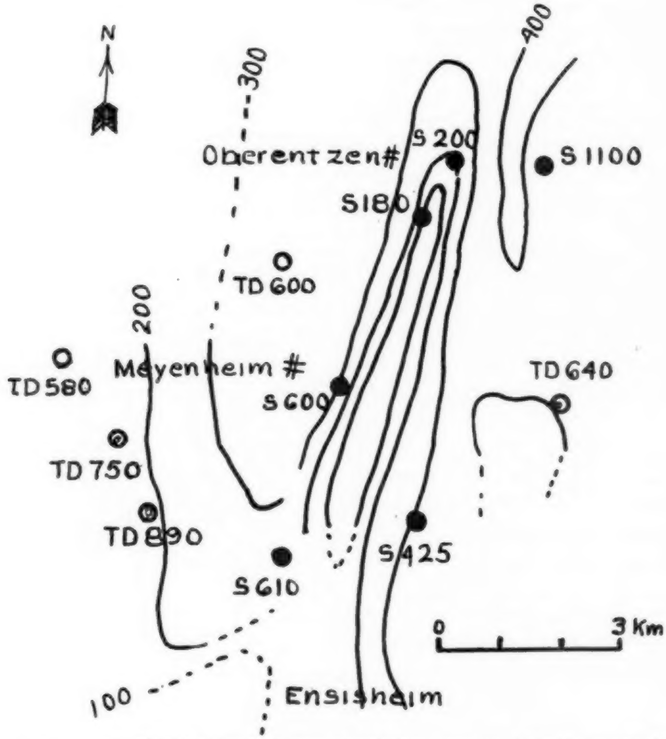


FIG. 1.—*D*. Electrical method, map of resistivity over the Meyenheim salt ridge in Alsace. (After Carratte and Kelley)

The maps and profiles of the distribution of the various physical effects such as the illustrations of Figure 1 are maps and profiles of purely physical quantities, not of geological quantities, and the physical effects must be translated to be understood in terms of geologic structure. Isogam maps in gravitometric or magnetometric work seductively resemble structure-contour maps, but they are maps showing lines of equal gravity or magnetism and not lines of equal elevation on structure. It is only rarely that there is close correspondence between the isogam and structure-contour maps. The skilled interpreter may be able to translate at sight the general sense of the physical effects into terms of geologic structure. Nevertheless, there is a definite act of translation in his mind; or he may have to go through a series of mathematical calculations to decipher the sense of the physical effects in terms of geologic structure.

SUBSURFACE PHYSICAL PROPERTIES

The physical effects mapped at the surface depend on the variation of the distribution of physical properties in the subsurface. The surficial variation of the intensity of gravity depends upon the variation of density in the subsurface; the travel time of elastic earth waves from the shot points to the receiver stations depends upon the distribution of velocity of transmission of the waves in the subsurface; and similarly for the other effects. From observed variation of the physical effects at the surface, certain conclusions can be drawn in regard to the variation of the distribution of the corresponding physical property in the subsurface. The second step in a geophysical method is the interpretation of the distribution of the physical property in the subsurface on the basis of the data of the observed variation of the physical effect at the surface.

The gravitational methods depend on the variation of mass, that is, of density, in the subsurface. If a part of the earth's crust is entirely homogeneous, the lines of the vertical[1] are straight vertical lines, and the level surfaces[2] are plane horizontal surfaces, by definition everywhere perpendicular to the lines of the vertical. If an extra heavy mass is present, as in Figure *2B*, the lines of the vertical bend in toward the heavy mass, that is, if a body is thought of as falling freely close to the heavy mass, the attraction of the heavy mass pulls the falling body slightly inward. As the level surface must everywhere be perpendicular to the lines of the vertical, the level surfaces arch up over such a heavy

[1]The path of a freely falling body is a line of the vertical.

[2]The surface of a body of water at rest or a surface of constant elevation.

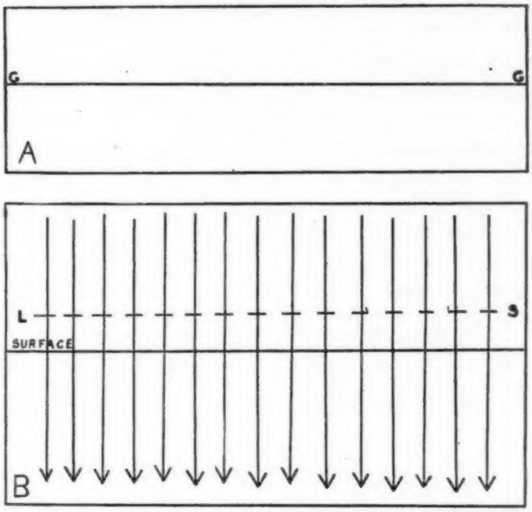


FIG. 2.—Diagrammatic vertical sections showing the variation of the intensity of gravity (*G-G*) of one level surface (*L-S*), and of the lines of the vertical for a small segment of the earth's crust. From "The Eötvös Method of Mapping Geologic Structure." *Amer. Inst. Min. Met. Eng. Tech. Paper 50* (1928).

A. With no variation in density.

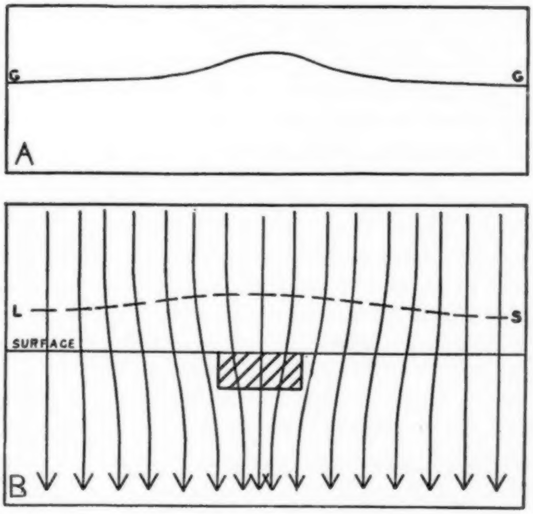


FIG. 2.—*B*. With an extra heavy block present within the earth's crust.

mass. If the mass were extra light instead of extra heavy, the lines of the vertical would curve away from it and the level surface would bend down above it, as in Figure 2*C*. As an extra heavy mass adds a little additional pull to the gravity, the intensity of gravity increases to a maximum above the center of the extra heavy mass (Fig. 2*B*), and the rate of increase, that is, the horizontal gradient of gravity, is at a maximum approximately over the edges of the heavy mass (Fig. 3*A*). If the body is extra light, it reduces the pull of gravity correspondingly, and the value of gravity decreases to a minimum immediately above the center of the extra light mass (Fig. 2*C*) and again the gradient is at a maximum approximately above the edge of the extra light mass and becomes zero and changes sign above the center (Fig. 3*B*). If the extra heavy mass is a horizontal plate-like body, infinite in three horizontal directions and terminated by a vertical face in the fourth, as in Figure 3*C*, the intensity of gravity increases from a minimum at infinity on the left to a maximum at infinity on the right, and the rate of increase, that is, the horizontal rate of gravity, increases from zero at infinity on the left to a maximum immediately above the vertical face and decreases to zero at infinity on the right. If the face of the plate is inclined, the gradient profile becomes asymmetric (Fig. 3*D*). If the extra heavy mass is in the form of asymmetrical anticline, it produces a gradient profile similar to that in Figure 3*E*. If the anticline is asymmetric, the gradient profile likewise is asymmetric.

From the distribution of the variation of the gradient and the differential curvature of the torsion-balance survey, certain conclusions can therefore be drawn in regard to the distribution of density in the subsurface. If a gradient profile similar to that of Figure 3*C* is mapped, the interpreter immediately knows that he is dealing with a vertical scarp with the heavy mass on the right and not on the left and he has formulae which give him a fairly close approximation to the depth of the heavy mass. If the gradient is in the opposite direction, he knows that the heavy mass is on the left side, and not on the right. If a gradient profile similar to that of Figure 3*A* is mapped, the interpreter immediately knows that he is dealing with a buried block or anticline and from certain differences in the character of the profile, he recognizes whether it is a prismatic block as in Figure 3*A* or an anticline as in Figure 3*E*, and the differential curvature measured by the torsion balance tells certain things about the amount and convexity or concavity of the curvature of the level surfaces (Figs. 2*B* and *C*) and from it as from the gradient, the interpreter can draw certain conclusions or make semi-quantitative

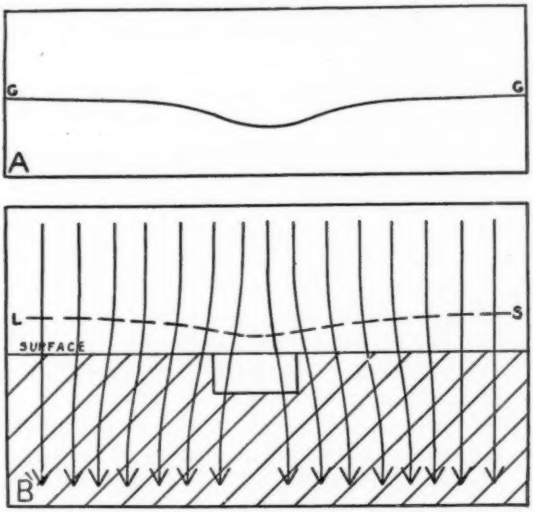


FIG. 2.—*C*. With an extra light block present within the earth's crust.

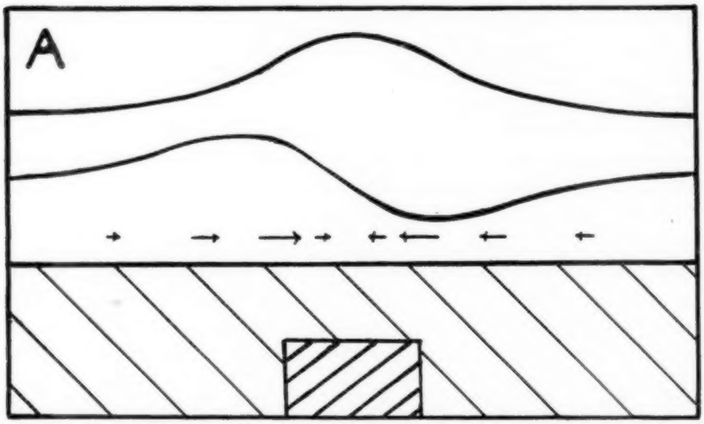


FIG. 3.—Diagrammatic vertical sections and profiles showing the variation of the intensity of gravity (upper profile) and the variation of the horizontal gradient of gravity above extra heavy or extra light bodies of different shape.

A. Above an extra heavy prism.

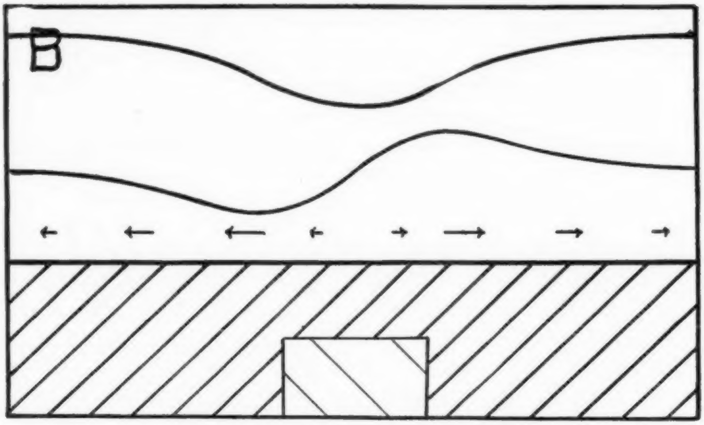


FIG. 3.—*B*. Above an extra light prism.

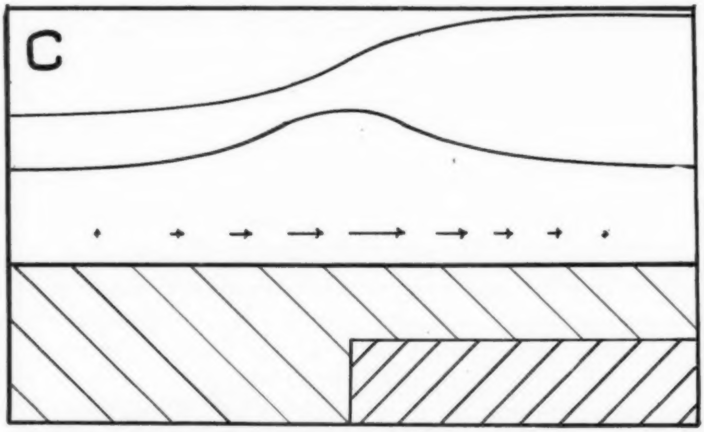


FIG. 3.—*C*. Above an extra heavy horizontal plate infinite in three horizontal directions and terminated by a vertical face in the fourth direction.

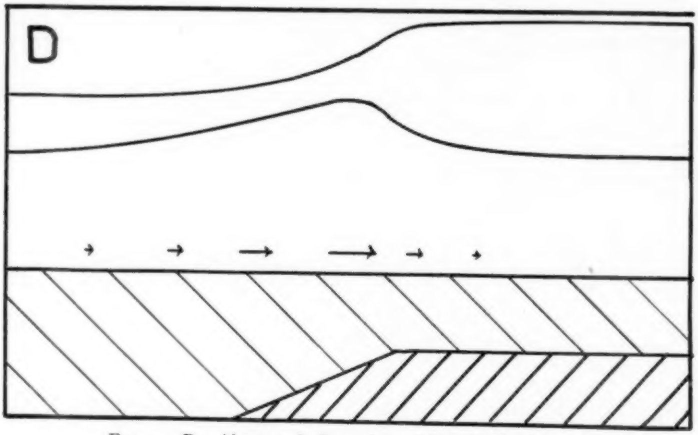


FIG. 3.—*D*. Above a similar prism with an inclined face.

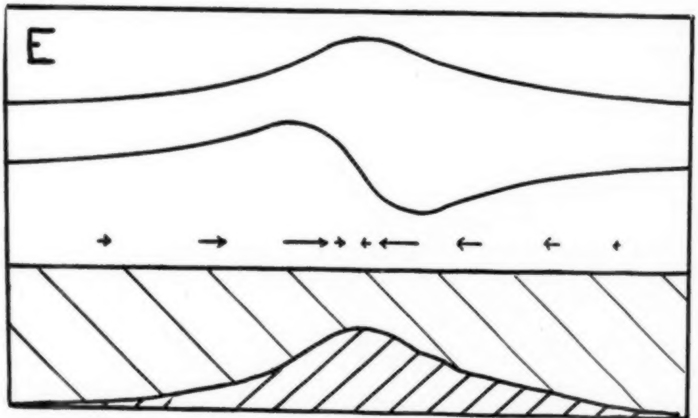


FIG. 3.—*E*. Above an anticlinal ridge of extra heavy density.

calculations in regard to the form and position of extra heavy or extra light masses in the subsurface. If the sign of the gradient had been reversed in the profile, the interpreter would have known immediately that he was dealing with a block of density less than normal rather than one of density heavier than normal.

Mathematically, each body tends to have a unique distribution of the variation of the gradient and differential curvature, but practically, the observed values of any survey have a larger probable error than the difference between the distributions produced by a considerable suite of bodies of somewhat different shapes and densities. There is, therefore, considerable uncertainty in the determination of the distribution of density which is producing the observed variation of the gradient even if the anomalous mass has a simple geometric form. Few geologic bodies have a simple geometric form, and in few conditions is only one anomalous mass present. The greater the number of elements that make up the structure, the greater, of course, is the uncertainty in the interpretation of the distribution of density in the subsurface; and in general, the interpreter will at best be able to give only outlines of a generalized mass of composite density to account for the variation of the gradient and differential gravity which he has mapped. In special situations, particularly on faults in rather simple stratigraphic sections, or possibly on salt domes, the geophysicist can give fairly accurate, quantitative predictions in regard to the distribution of density, but more generally he is able to say, for example, merely that an anticlinal-shaped mass is present at depths ranging from 1,000 to 2,000 feet or perhaps from one mile to two miles, or to make some other similarly more or less indeterminate prediction.

In the seismic method, if the crust is entirely homogeneous, the elastic earthquake produced by the explosion travels at a constant rate of speed in all directions. The explosion wave which arrives at a seismograph travels essentially just below the surface and is known as the "surface" wave. The time it takes for the "surface" wave to travel from the explosion point to the seismograph is directly proportional to the horizontal distance between the shot point and the seismograph point. A travel-time-distance graph where the travel time is plotted against distance, therefore, is a straight line as the line T_1 in Figure 4. If, however, there is a higher speed bed present in a subsurface beyond a certain distance, the situation may be compared with the travel time for an auto trip from town *A* to town *B* (Fig. 5). If the towns are connected directly by a poor dirt road, if there is a good concrete pike or highway,

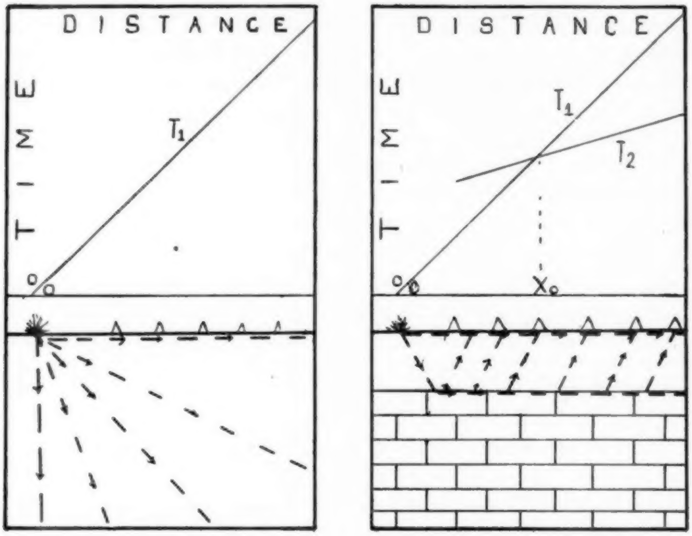


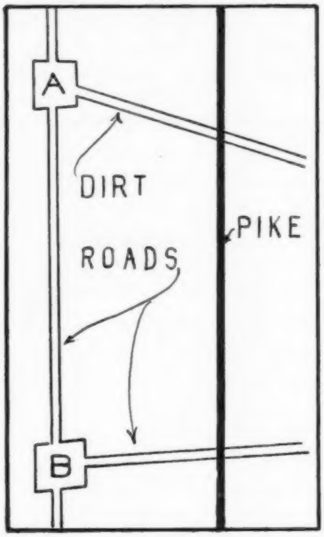
FIG. 4.—Diagrammatic representation of travel-time-distance graphs and paths of the explosion waves used in the "mirage" method.

A (left). With no variation in speed of transmission of the explosion waves.

B (right). With a relatively high-speed bed underlying a relatively low-speed cover.

T_1 represents the travel-time-distance graph of the "surface" wave and T_2 of the refracted wave. X_0 is the distance from the shot point to the point where T_1 and T_2 intersect.

lying slightly south of the two towns, and if the towns are far enough apart in reference to the distance south to the pike, the quickest automobile time from *A* to *B* is south to the pike, along the good concrete road, then north to town *B*. If, however, the distance between the towns is not great compared with the distance south to the concrete road, the trip via the direct, dirt road is the quickest. In a similar way, the wave which takes a path diagonally downward to the high-speed bed, travels along a surface for a distance, and comes diagonally up to the receiving point, makes faster time than the surface wave, provided that the distance between the shot point and the receiving point is sufficiently large in reference to the depth of the high-speed bed and in reference to the relative velocities of the two formations. If a high-speed bed is present in a subsurface, the travel-time-distance graph shows line T_1 as before, and in addition, line T_2 (Fig. 4*B*), giving the travel time of the wave



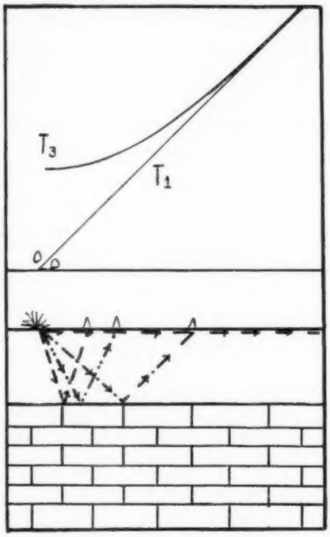


FIG. 5 (left).—Sketch map showing two towns *A* and *B* lying off a pike and connected with it and with each other by mud roads.

FIG. 6 (right).—Diagrammatic representation of the travel-time-distance graphs and paths of the explosion waves used in the reflection method. T_1 represents the graph of travel-time-distance for the "surface" wave again, and T_3 for the reflected wave.

which went down to the high-speed bed, traveled along its surface, and came up. From the slope of line T_1, the velocity of transmission of the elastic earth wave is given for the upper bed and from the slope of line T_2, the velocity for the lower high-speed bed. By the use of the distance X_0 to the point at which the travel time is the same for both wave paths, a formula involving also the velocities of the two formations gives the depth to the high-speed bed. If the high-speed bed is not horizontal, but is dipping, profiles shot in reverse directions allow the determination of the velocity of the two formations and the dip and depth of the high-speed formations to be calculated by somewhat more complicated formulae. If the high-speed bed is discontinuous, the discontinuity produces certain variations in the character of this travel-time-distance graph and by the use of proper formula and data from the graph, the position of the edge of the scarp can be calculated. An apparently more simple method is to observe the direct reflection of the elastic earth

waves from the top of the high-speed bed as in Figure 6. In the diffraction method which has just been described, the refracted wave, which is the critical factor, comes in before the surface waves. In the reflection

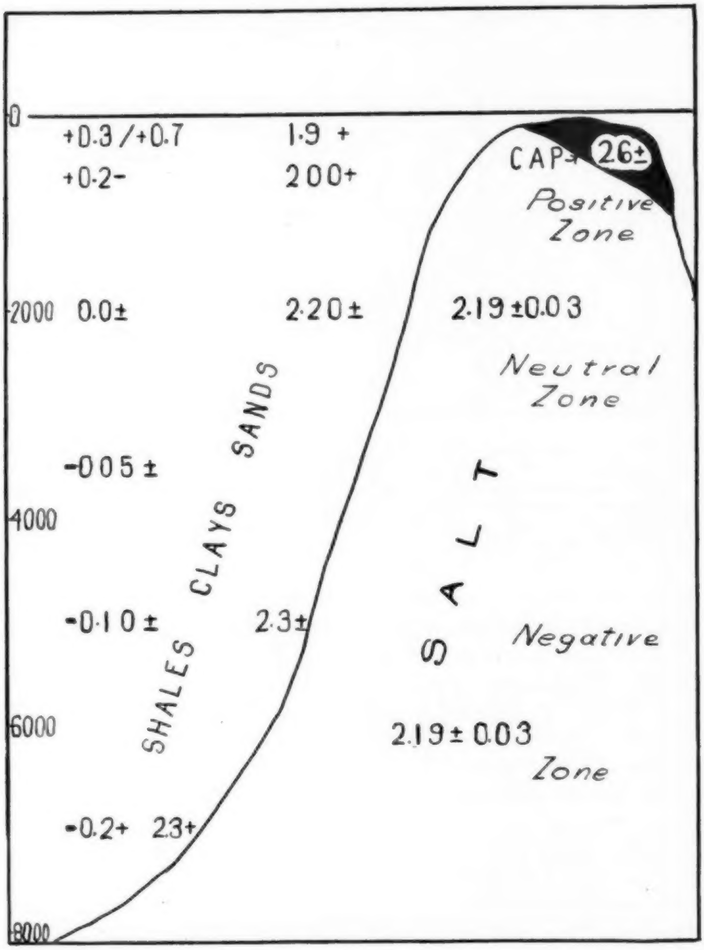


FIG. 7.—Diagrammatic vertical section showing the idealized density relations of a Gulf Coast salt dome. The figures from 1.9 to 2.6 give the specific gravity of the sediments, salt, and cap rock and from −0.2 to +0.7 give the specific gravity differences between the salt or cap and the sediments.

method the reflected wave (T_3, Fig. 6) comes in after the surface wave (T_1, Fig. 6); it is, therefore, mixed up with the train of after-waves. The reflection method is gradually coming into more and more use. The velocity of the upper formations can be measured by dropping an electric seismograph down a deep well, or slightly more approximate determinations can be made from the surface, and if the velocity of the formation is known and the distance between the shot point and receiving point is known, the calculation of the depth to the high-speed bed is given by a simple formula.

Abnormally magnetic bodies in the subsurface produce a variation in the intensity of magnetism, in many ways similar to the variation of the gravitational field. An abnormally magnetic mass in temperate latitudes produces an increase in the vertical intensity which is at a maximum above the abnormally magnetic body, and conversely, if the body is less magnetic than the surrounding country rock, it produces a minimum of vertical intensity immediately above the body. Theoretically, there is a certain degree of unique correspondence between the form and depth of the abnormally magnetic body, and the type of surficial distribution of the variation of the vertical and horizontal components, and conversely, it is possible to draw possible conclusions from observed variation of intensity of the surface in regard to the form and depth of the anomalously magnetic mass, whether more or less magnetic than the surrounding country rock. These determinations, however, are much more indeterminate and indefinite than the determinations from gravity surface.

In the electric methods, likewise, there is a certain degree of unique correspondence between variations in conductivity-resistivity in the subsurface and the electro-magnetic fields at the surface. Certain conclusions can be drawn in regard to the presence of good or bad or relatively bad conductivity contained in the subsurface, its distance, position, continuity, or discontinuity. The conclusions, however, may be exceedingly weak.

INTERPRETATION OF GEOLOGY

From his conclusions in regard to the distribution of one or more of these physical properties in the subsurface, the geological geophysicist can draw certain conclusions in regard to the presence and character of geologic structure, thereby completing the third and last step in the operation in any one of the geophysical methods of mapping structure. The first step was to map the surface distribution of some physical effect. The second was to use the results of that mapping to determine

the distribution of some corresponding physical property. The third step is to interpret the geological situation corresponding with that property. In a fourth but entirely non-geophysical step, the petroleum geologist takes structure predicted by the geophysicist and draws his conclusions in regard to the possibilities and probabilities of the occurrence of oil on structure of that type.

The interpretation of geologic structure from the distribution of physical properties in the subsurface is based on the preliminary assumptions of (1) initial horizontal uniformity and vertical variation of the physical property, and (2) deformation of the physical property concomitant and corresponding with the deformation producing structure.

We must make the assumption that if no structure were present, there would be no horizontal variation in the distribution of the physical properties which we must use. We must, also, assume that there is some vertical variation in the distribution of the physical property; otherwise, structural deformation would produce no variation in the distribution of the physical properties. If, however, there is a horizontal uniformity and vertical variation present, a structural deformation of the beds produces a corresponding deformation of the distribution of the physical property.

An increase of density downward is shown rather commonly in many of the oil-producing areas. In a thick section of sands and shales, the older and more deeply buried beds show slightly greater compactness; therefore, higher density than the overlying beds. It is not uncommon, also, to find a thick section of sands and shales overlying a massive section of limestones or an igneous or metamorphic basement. The sediments are lighter than the limestone or the igneous or metamorphic rocks. Structural deformation of the type producing petroliferous structure uplifts the deeper, therefore denser, beds into the levels of higher and lighter beds and these uplifted deeper beds are normally in the core of structural "highs." Structural "highs" rather commonly, therefore, are gravity "highs" and if the geological geophysicist knows that he is dealing with an area in which there is the normal increase of density downward, he can interpret definite gravity "highs" as indicating the presence of structural "highs," and from the form of the distribution of density in the subsurface, he can make certain conclusions in regard to the character of the structure. If, for example, he has mapped a gradient profile such as that of Figure 3*C*, he knows that he is dealing with a fault, and from his knowledge of the heavy beds probably present, he can come to certain conclusions about the fault, and its amount of throw. If he

has a profile like that of Figure 3*E*, which he has interpreted as a distribution of extra density, somewhat like that of Figure 3*E*, he recognizes the presence of an anticline. From a mass such as that of Figure 1*A*, he recognizes the presence of an abnormally heavy mass in the shape of a truncated cone which might be either a laccolith or a salt dome. From his knowledge of the general geology of the area and the probability of the occurrence of salt domes and laccoliths, he makes his conclusions. In the Gulf Coast salt-dome area, he would say unhesitatingly that it was a salt dome.

The reverse density situation, however, may be present and massive beds of less density may lie below those of greater density, as in the case of a thick salt section at depth. The specific gravity of salt is 2.19 ± 0.03 and the specific gravity of the older Tertiary and of the Cretaceous sediments commonly ranges from 2.2 to 2.4. The salt series, therefore, is distinctly lighter. A salt anticline or a salt dome in the older Tertiary or in the Cretaceous rocks, therefore, produces a gravity minimum, and in a situation of this type, it is the gravity "lows" which are associated with the presence of structure.

The Gulf Coast salt domes commonly produce both a gravity "high" and a gravity "low." A dome rising to within a few hundred feet of the surface commonly is capped with a limestone-gypsum-anhydrite caprock mass of an average density of 2.6. The density of the salt mass ranges from 2.16 to 2.22 and should show little variation with depth. The specific gravity of the first few hundred feet of the sediments is 1.90 and theoretically, by compaction, it should increase to 2.3 or 2.35 at a depth of many thousands of feet. The upper part of the salt core together with the caprock mass produces a gravity maximum immediately above the top of the salt core. The deep parts of the dome, ranging from 4,000 to 6,000 feet down to the great depths, produce a gravity minimum. In the Gulf Coast salt-dome area, therefore, a small gravity "high" in a large gravity "low", indicating the presence of a conical or cylindrical mass heavier than the upper sediments and lighter than the lower sediments, is immediately recognized by the geological geophysicist as a salt dome lying fairly close to the surface. If, however, the gravity "high" is missing and only a large gravity "low" has been mapped, the geological geophysicist recognizes the presence of a rather deep-seated mass of less density than the surrounding sediments and recognizes the presence of a deep-seated salt dome not rising so close to the surface. In some places the geological geophysicist maps a mass somewhat like that in Figure 3*B* which he determines as an elongated semi-prismatic mass

lighter in density than the surrounding country rock. There are two possibilities: either this is a block of upper and lighter rocks faulted down, or it is a mass of lower and lighter rock which has been faulted up. The physics and mathematics of the situation make either condition possible. But from his knowledge of the geology of the situation, the geological geophysicist draws his conclusions and in one region interprets this anomaly as a down-faulted block, and in another region interprets it as an up-faulted block. If the geology of the region is unknown to him, he can merely guess that in general the possibility of a down-faulted upper, lighter block is greater than the probability of an up-faulted lighter block.

The seismic method works on discontinuity between relatively low-speed and relatively high-speed beds in the subsurface. Many beds can be recognized by the velocity. In the Gulf Coast, any mass of rock showing a velocity ranging from 16,000 to 17,000 feet per second and rising within 6,000 feet of the surface, is recognized as a salt core of a salt dome. In regions of massive igneous rock, similar velocities are possible, but in the Gulf Coast, the geological geophysicist knows that the salt is the only formation at that relatively shallow depth which has that high velocity. Some formations in the Gulf Coast likewise tend to have characteristic velocities; for example, there is a 7,500 feet per second bed and an 11,500 feet per second bed which are used in the seismic work and which the seismic geophysicist can recognize. In contour mapping with the seismic method, the seismic geophysicist picks out such a surface of discontinuity as the upper contact of the 7,500 feet per second semi-high-speed bed with the overlying 6,500 feet per second lower-speed bed. To the physical geophysicist, this contact is merely a surface of discontinuity between speeds of propagation of the elastic earth waves. The geological geophysicist knows, however, that this surface of discontinuity tends to coincide with the surface of some formation and that in general in mapping the conformation of the surface of discontinuity, he is mapping structure contours on some geologic key bed.

The philosophy of the interpretation of the geologic structure from the magnetometric survey is very much the same as in gravitometric work. In the absence of structure there is assumed to be a vertical but not a horizontal variation of magnetic material, and rather commonly the basement of metamorphic and igneous rock is assumed to have a uniform content of magnetic material larger than that of the overlying sediments. Uplifts of the basement, therefore, tend to produce "highs" in the intensity of the vertical component. In northwest Louisiana and

southwest Arkansas, the surface geologic formation contains much iron and in places carries low-grade iron ore. The underlying formations contain much less magnetic material. In that area, therefore, structural "highs" are represented by magnetic "lows." In most areas, the geological geophysicist intreprets an anomalous mass with magnetic material less than normal, as a structural depression of some sort, but in northwest Louisiana and in southwest Arkansas, he interprets it as a structural elevation.

Interpretation of geologic structure by electric methods is similar in general principles. The geological geophysicist knows that the possible types of structure in the particular area produce certain types of distribution of conductivity and conversely, he is able to make certain conclusions in regard to the geologic structure present. In some places he is able to map the surface of some bed of especially good conductivity which, as a geological geophysicist, he is able to recognize as extremely saline water in some particular bed; or from the aspect of the distribution of this zone of very good conductivity, he is able to recognize that it must be cutting across stratification and must represent saline waters rising along a fault or fissure.

In all this interpretation of geologic structure, something must be known of the geologic situation of the area. The physical geophysicist can take the field observations of the surficial variation of the physical effects and can draw his conclusions in regard to the distribution of the physical properties in the subsurface, but in general, there is a range of greatly differing geologic situations which produce such a distribution of physical properties. But, in general, in any area, there may be only one possible geologic structure or in some places, two structures, to give the correct distribution of the physical properties in question,—with a density, content of magnetic materials, speed of transmission of elastic waves, and electric conductivity to give the variation of the distribution of the physical effect at the surface. Knowing the geologic possibilities and probabilities of such geologic structure in the area, the geological geophysicist can make his definite conclusions or his shrewd guesses, or in some places, his wide guesses in regard to the probable structure which is indicated by the observed variation of the physical effects.

When the geological geophysicist has made his interpretation of the probable structure that is present, the geologist can then make his broad guess in regard to the favorableness of the structure for oil. This broad guess is not based on geophysics, but is based on the assumption that the geological geophysicist's interpretation of the structure is correct,

and upon the geologic knowledge of the geologic occurrence of oil in this particular area and the geology of the occurrence of oil in reference to structure. The geologist's conclusions in regard to the favorableness of the structure for oil are made in the same way as if the structure had been determined by the older methods of mapping geologic structure, and in no way involve geophysical data except that indeterminateness and indefiniteness in the geophysicist's conclusions necessarily involve corresponding indeterminateness and indefiniteness in the petroleum geologist's conclusions. The conclusions of the geologist favorable for the possible occurrence of oil must then be checked by drilling, which still is the only known method of finding whether oil actually is present in the subsurface in commercial quantity.

LIMITATIONS OF GEOPHYSICAL METHODS

All geophysical methods have their limitations and difficulties. The primary assumption of all these geophysical methods is that there is concordance between structure and the distribution of physical properties. This concordance is perfect in few places, and may be almost entirely absent. The preliminary assumption of initial horizontal distribution of physical properties may be only partly true. A formation may grade laterally from the very light salt to the very heavy anhydrite, or it may grade from a relatively light sand and shale section into a massive limestone section. An up-faulted block of massive limestone may be brought up into other massive limestones or a buried granite ridge may be mantled with limestone and in such conditions, there may be no relation between the distribution of density and the structure. There may be a thick massive section of sediment without any special difference of density. Deformation of the structure, therefore, will not produce any deformation of the distribution of density. The variation of specks of magnetite throughout the formation vertically and horizontally may be dependent wholly on the conditions prevailing at the time of deposition and if deformation takes place, there may be no relation between the distribution of magnetic content and structure. In seismic work, the surface of discontinuity between the upper relatively low-speed bed and the lower relatively high-speed bed may not everywhere represent the same stratigraphic plane; two formations of the same velocity may be faulted together so that the upper surface of one is a prolongation of the upper surface of the other, or the upper surface of one formation may grade, within a short distance, from limestone to shale; thus, in one place the seismograph is working at lower stratigraphic level in the for-

mation than it is at other places. A high-speed formation may be composed of several members: if the upper member has been eroded or was not deposited locally, the seismograph runs on the top of the second member without recognizing the drop, and generally, if the first and second members happen to be absent locally, the top of the third member serves as the surface of discontinuity. If the top of an up-arched formation has been beveled by erosion, the erosion surface is a surface of discontinuity which has no relation to the underlying structure. In electric methods, various conditions are possible which produce variations of the distribution of conductivity which have no relation to the geologic structure.

Lack of knowledge of the geophysical constants of formations is an added difficulty and limitation in the use of the methods. The physical constants of hand specimens can be determined. Samples of the outcrop of a formation or samples from a well may be taken to a laboratory and their specific gravity, magnetic permeability, elastic properties, and resistivity can be measured and the physical constants of those particular hand specimens determined. Formations, however, are not homogeneous and a hand specimen is characteristic only of a very small part of the formation. A very complete vertical and horizontal suite of hand specimens allows a fairly close approximation of the physical character of the formation at that point. But the physical character of formations varies horizontally and the physical character of a formation at its outcrop is considerably different from that down deep where the rock is not exposed to the alteration of wet and dry, heat and cold, and evaporation and deposition of cementing materials in the pore spaces. Few cores are taken continuously in drilling, and samples available from the subsurface for testing are few and far between, both vertically and horizontally. What may be spoken of as the geophysical constants of a formation may be contrasted to the physical constants of a hand specimen. Although somewhat heterogeneous, a specified formation has a fairly constant mean specific gravity in one locality and this mean specific gravity may be spoken of as the geophysical constant of the formation. The geophysical constant could be obtained if samples were obtained in infinite number and the physical constant determined for each of the samples. The geophysical constants, as a practical matter, can be ascertained in many places if sufficient field work has been done, with supplementary aid from the determinations of the physical constants of whatever samples are available. In a new area, for example, by a certain technique of profile shooting and if possible, by dropping his

geophones to the bottom of deep wells, the seismic geophysicist has to work out a new series of velocities for his formations and keep correcting them as his experience with the formations progresses; similarly with the magnetic and electric methods. To a considerable extent, as a particular example in the magnetic method, the geophysical magnetic constants for formation are entirely unknown and can not be determined and the geophysicist merely knows that apparently certain deeper formations, probably in the basement, have a somewhat higher magnetic permeability than the overlying formations. Yet, in all interpretation, the geophysical constants must be taken into consideration. The seismic geophysicist can not make any assumptions in regard to depth unless he uses some assumption at least in regard to the velocity of the formations through which his elastic earth waves have traveled. In interpretation of torsion-balance results, the geophysicist must make certain assumptions in regard to the density situation which he uses to make anything but a very crude qualitative interpretation and if different density assumptions are used, differently shaped geophysical bodies may produce the same distribution of physical effects.

Irregularities in the distribution of density, magnetic material, electrical conductivity-resistivity, or ground tremors near the observation station may produce errors which may be serious. Topographic irregularities produce gravitational irregularities for which corrections can be calculated if the topographic irregularities are not too rugged and too irregular. Boulders and other concealed irregularities of density in the subsoil near the torsion balance may produce serious gravitational irregularities for which no correction can be applied. Similar difficulties apply to the magnetic method and in addition, casing in wells, pipe lines, high-power electric lines, and iron keys in the observer's pocket may produce irregularities which preclude satisfactory magnetometric observations. Local irregularities of resistivity immediately at the point of introduction of the sounding electrodes produce serious difficulties in certain types of the electric methods. Ground tremors ordinarily can be eliminated in seismic work by reducing the amplification, increasing the charge of dynamite, and by filters, but in special situations such as near the shore when heavy surf is running or in a community where there is continuous and heavy traffic, it may not be practicable to eliminate the ground tremors. The wind conditions may produce irregularities in the travel time of the sound wave which is used by the seismic geophysicist to determine the distance between shot point and receiver point.

Lack of known geology and incorrectness of the geologist's conception of the geology add to the difficulty and limitations of the geophys-

ical methods of prospecting. The geophysicist can not entirely reason out the reactions of all types of geological bodies. He can reason out the reactions of simple geometrical bodies, but few geologic structures and situations are simple, and all the factors entering into the situation are not known. In a general area, however, certain groups of the factors commonly are rather constant and by the proper checking of geophysical surveys against known geology, the geophysicist can learn partly by experience, partly by theory, how his methods react to certain types of structure and evaluate the degree of reliability of the methods in that area. If the geologist mistakenly identifies a known fossiliferous Pennsylvanian limestone as a stratigraphically much deeper Ordovician limestone and the geophysicist tries to check his method in his map of structure of that particular area against the geologist's structure map, the geophysicist will be unable correctly to evaluate the reaction of his method and both the geologist and the geophysicist may get a false value of the method in that area. A certain amount of knowledge of the geological possibilities and probabilities of an area is necessary for the interpretation of most geophysical work. If the geologist's knowledge of the area is lacking, or contains seriously erroneous conceptions, added uncertainties and difficulties are thrown into the interpretation of geophysical work. The geophysicist may be able to recognize that there is something wrong if his interpretation does not agree with the geological interpretation of a little known situation, but he may not be able to tell what is wrong.

What seem probably to be heterogeneities in the basement complex add considerable difficulties to the interpretation of torsion-balance and magnetometer surveys. Large regional anomalies, both gravitational and magnetic, are being mapped which geophysicists are coming to believe can be explained only by irregularities within the basement complex, in many places by large batholithic intrusions. We can find nothing in the upper section which would seem competent to produce them, and judged by their physical relations, they can easily be large-scale bodies lying well down in depth and well within the basement complex. Relief on the basement itself may in many places add to the difficulties of interpretation of shallow structures.

Inexperience, even among the best geophysicists, is an added limitation and a difficulty in the use of the methods. All of the geophysical methods of prospecting for structure are relatively new and have been extensively used for less than five years. If the best petroleum geologist of fifteen years ago, with the knowledge of that date, were turned loose in

a modern geological department, he would not know what to do with many of the data which the modern advanced petroleum geologist uses, and it would take the geologist of fifteen years ago some time to learn what it has taken the geological profession fifteen years to learn. Many of the indications of structure that to-day are thought fully to justify prospecting would not have been recognized even as mildly suggestive fifteen years ago. In the past fifteen years, oil geologists have learned much from practical experience. Fifteen years ago, the "Big lime" was the farewell horizon in Oklahoma, and any geologist who would have foretold the gusher production of Seminole would have been laughed at. It is not many years ago that there was "no possibility of production from West Texas or from Arkansas." The oil geologist is learning much with experience and knows much more about finding oil than he did fifteen years ago. It is the same way with the geophysicist. He is in much the same situation of experience and evolution that the oil geologist was in fifteen years ago. His methods must be used extensively in different areas before he can accumulate a sufficient background of practical experience to become as competent in interpreting his geophysical data as the geologist is in interpreting his geological data. The geophysical methods of prospecting for petroliferous structure have been used more extensively in the Gulf Coast than anywhere else in the world, and the geophysicist can interpret more from his data in the Gulf Coast than he can in practically any other petroleum province, but even here, we are constantly learning to read more and more from our data and to do things with our methods which we could not do in the previous year.

DIRECT PROSPECTING FOR OIL

The geophysical methods which have been discussed are indirect methods of looking for oil. On account of the extremely high resistivity of oil, there is a bare chance theoretically that some electrical method will be devised directly to detect the presence of petroleum. The resistivity of petroleum is rated in millions of ohms in contrast to a few hundred thousands of ohms in the ordinary, less conductive formations. Certain geophysicists, therefore, assume that the oil sand should stand out with an enormously high resistancy compared with the surrounding medium. There are certain geological doubts about the correctness of this assumption. Although strong assertions are made that oil can be, even has been, found directly by one method, geophysicists as a whole do not accept these assertions as proved and feel rather doubtful whether

any practical field working method of direct determination of petroleum will be devised. There is, however, a faint theoretical possibility. The drill still is the only direct method of determining the presence of oil in the subsurface.

CONCLUSION

The geophysical methods of prospecting for oil, therefore, are far from being the ultimate means of discovering petroleum. They are only an indirect method of searching for petroleum, and at that, really only a doubly indirect method. Strictly, at best, they map the distribution of some physical properties in the subsurface. The geological geophysicist, on the basis of his knowledge of the geology of the area, the concordance and lack of concordance of the structure, and the distribution of these physical properties, makes more or less shrewd guesses in regard to the probable structure, and just as there is no hard and fast law of concordance between the occurrence of oil and structure, there is no hard and fast concordance between the distribution of any of these physical properties and geologic structure. The geologist may map a very pretty anticline in a region where oil should be present, but he does not predict in advance of drilling, the definite occurrence of oil on that structure. By simple theory, oil and gas should be found on the crest of the structure, but without any indications of the fact at the surface, the reservoir sands may have been eroded, may have been lensed out, or have been cemented to an impervious sandstone over the crest of the structure, and the crest of the structure may be entirely dry, and instead of the oil being on the crest, it may be found only well down on the flanks. The geologist can only indicate in general that the crest of that anticline is the most favorable point to expect the occurrence of oil; therefore, the most favorable point on which to drill in search for the oil. Similarly, in general, the geophysicist can merely indicate that his gravity "highs," or in some places, gravity "lows," most probably represent geologic structure, and in the absence of more definite data, the gravity "high" is the most favorable place to drill. His method is a somewhat indirect method of mapping the distribution of physical properties in the subsurface. He may map the surface distribution of the physical effects with a high degree of accuracy, but in the absence of knowledge of the geophysical constants of the subsurface, he may not be able to evaluate the distribution of the physical properties in the subsurface. Like oil geology, the geophysical methods of prospecting tend to reduce but in no way eliminate the risk in the search for oil. Like the geologic methods of mapping structure, the several geophysical methods are of great service in

certain areas, are of slight service in some, and are valueless in other areas. In the Gulf Coast, the seismic and torsion-balance methods have worked brilliantly and have had great success, but even there, they have had their failures, and have their limitations; the electric method may work on salt domes, but seemingly can not compete either with the seismograph or the torsion-balance methods; the magnetometric method might be better than surface geology methods, but its results are so uncertain compared with the other methods that it is useless. In certain problems in other areas, however, such as the determination of the absence of a volcanic block under a surface structure, the magnetometric method works excellently. The other methods have similar limitations. One geophysical method may be sufficient in mapping a certain area. In other places, it may be advisable to use a comparison of methods. In some areas, it may be a waste of money to use any geophysical method and in other areas, for example, the Gulf Coast, it may be a waste of money to prospect for new structure without the use of geophysics. If significant surface geology can be mapped, the geophysical methods of prospecting in general should not be used, because in general the data from geophysical prospecting are less definite than good surface geology. This statement, perhaps, should be qualified for the situation where there is a very considerable unconformity at moderate depth, and the oil man may be interested in the unconformity. In such a place, geophysical methods of prospecting may give a key to the subsurface geology. Although they are no panacea for the difficulties of oil finding, the geophysical methods of prospecting for the oil-bearing types of structure have demonstrated that they have a permanent and considerable place in oil geology.

GEOLOGICAL NOTES

NOTE ON THE "*BULIMINA JACKSONENSIS* ZONE"[1]

There has been doubt in the minds of Gulf Coast paleontologists as to the true position of the *Bulimina* zone of the Jackson in relation to the *Textularia dibollensis* zone of the Jackson.

This has in a measure been cleared up by the occurrence of these two fossils in the same samples from the Humble field, Harris County, Texas. This fact led to further inquiry into samples of approximately the same age. Similar fossils have also been found in samples from South Liberty, Liberty County, Texas. In both places the fossils are typical of the two species.

It might be well at this point to quote from J. A. Cushman and E. R. Applin's paper on the "Texas Jackson *Foraminifera*," published in this *Bulletin*, Vol. 10 (1926), pp. 154-89. In discussing the *Bulimina jacksonensis* zone the authors make the following statement.

> The true position of this zone has been disputed because its occurrence was first noted on domes in southern Texas. . . . In several instances it has been found below the *Textularia dibollensis* zone.

My conclusion is that the "*Bulimina*" zone is a horizon in the *Textularia dibollensis* zone in Texas and that the term "*Bulimina jacksonensis* zone" should be abandoned. *Textularia dibollensis* seems to have a much wider range geographically and should be used as a zonal name at the expense of *Bulimina jacksonensis*, which occurs in the lower part of the *Textularia dibollensis* zone in several places.

This note should not be regarded as critical of Cushman and Applin's paper in a destructive sense, as the writers of that paper admitted that the evidence regarding this was not well established.

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HUMBLE OIL AND REFINING COMPANY
HOUSTON, TEXAS
January 10, 1930

[1]Published with the permission of the Humble Oil and Refining Company.

[2]Introduced by Alva C. Ellisor.

SIMPSON *VERSUS* "DETRITAL" AT OKLAHOMA CITY

When a new pool is discovered, the producing horizons are immediately christened by the oil fraternity, very much as a new baby is named. This heritage of nomenclature usually comes from the nearest related pools. Development of a pool always brings out new facts which make some of the first ideas and correlations inaccurate.

The Oklahoma City field has its usual heritage of names: examples are the Pawhuska lime, the Carmichael lime, the Hoover and Tonkawa sands, the Oread lime, the Layton sands, the Checkerboard lime, the "Detrital zone," and the Arbuckle lime.

Many of these names were brought down from the Garber field, among them the "Detrital zone," which is the subject of considerable controversy at this time. The following comments are given, with the permission of the management of the Indian Territory Illuminating Oil Company, in the hope that they may clear up some of the arguments on the subject.

The word detrital, in its common usage, means a deposit produced by weathering or disintegration of rocks. Since practically all sediments are "detrital," except possibly those which are chemical or of a volcanic nature, to call any zone a "detrital zone" simply means that the person who first named it did not definitely know what the material was.

The "Detrital zone," so called, at Oklahoma City, has a thickness ranging from almost nothing to approximately 300 feet in the wells drilled at the present time, although some have not gone through the zone into the Arbuckle. From the nature of the material that has been called "detrital," it is noticed that it is fairly well bedded, if one divides it into zones by careful microscopic work. Individual beds, of course, are very lenticular, which is the chief characteristic of the Simpson formation on the outcrop. Therefore, zones of 2 or 3 feet can not be used. The material which has been called "detrital" consists of sandy dolomites, gray to buff, and in some places greenish, alternating with beds of sands containing dolomitic shales and bedded zones of bright green shale intercalated with sands, dolomitic sands, and sandy dolomite, and dark grayish green shales.

Many of the fossils found in the various parts of this "Detrital zone" are of such a nature that they could not have been transported very far without being destroyed, and the individuals represented must have died in place. These fossils indicate a certain age, but none of them found up to the present time is younger than the Lower Chazyan or

Simpson. This fact alone would preclude the idea, which so many have held, that the "Detrital zone" was derived from pre-existing hills which contained formations of different ages, such as seems to have been the fact with the "Detrital zone" at Garber, in which fossils of an age younger than the Simpson have been reported. Among a number of fossils which have been found, the following are indicative of Simpson age.

In the Indian Territory Illuminating Oil Company's Williamson-Canfield No. 1, located in the SW. ¼, SE. ¼, SE. ¼, Sec. 24, T. 11 N., R. 3 W., a core was taken from 6,313-6,318 feet. From a well bedded dove-colored dolomite at 6,315 feet, many perfect specimens of *Didymograptus artus* Ellis and Wood were found. These forms were also found from the Indian Territory's H. V. Foster No. 1, located in the center, SW. ¼, NE. ¼, Sec. 24, T. 11 N., R. 3 W., in a core taken between 6,302 and 6,312 feet. Graptolites have also been reported in a core at 6,481 feet from the Coline's Clauer No. 3, in the SE. ¼, SE. ¼, SE. ¼, Sec. 25, T. 11 N.,R. 3 W. Since all of the graptolites observed by the writer are of the same age and occur in well bedded material, it seems rather improbable that they should have been transported to the material in which they are found.

In the Indian Territory's Nettie Emerson No. 1, located in the SW. ¼, NE. ¼, NE. ¼, Sec. 30, T. 11 N., R. 2 W., a core which is a coarsely crystalline fossiliferous limestone, duplicating, in all respects, the Lower Simpson on the outcrop, was taken at 6,328 feet. In the core were found *Orthis* species, *Prioniodus* species, and *Leperditia*, a new species. This *Leperditia* is extremely plentiful in the lower 800 feet of the Simpson on the outcrop. Other forms found in profusion were scales and teeth of fishes.

The limestone containing these fossils is irregular in occurrence. In the Indian Territory's Wilkie Anderson No. 1, located in the NE. ¼, SE. ¼, NE. ¼, Sec. 25, T. 11 N., R. 3 W., a core was taken between 6,293 and 6,308 feet, which consisted largely of a very friable frosted sand. From 6,307 feet, the genus *Scolopodus*, represented by a new species, and other forms also closely related to the family *Distacodidae* were obtained. This core is from the upper part of what has been called "detrital," but it contains nothing that might indicate an age younger than the Simpson. From the Indian Territory's Warner-Speegle No. 1, located in the SW. ¼, SW. ¼, SW. ¼, Sec. 24, T. 11 N., R. 3 W., a core of bright green shale, interbedded with frosted sands and dolomites, was taken from 6,398-6,408 feet. The piece examined was from 6,407 feet and contained a species of *Acodus*, a species of *Drepanadus*, and a new

species of *Scolopodus*, which is similar to the species found in Wilkie Anderson No. 1. There were also many fish scales and plates present and a nepionic form of *Maclurea*.

The foregoing wells are characteristic and one might go into great detail concerning the samples from the other wells, which have also penetrated the so-called "detrital" zone. From the evidence yielded by the fossils and from the nature of the beds containing them, such as the character, interval, and stratigraphic position, it would seem advisable that the term "detrital" be no longer applied to this zone encountered in the Oklahoma City field. Everything seems to indicate that the age of this zone is Lower Simpson and that it does not represent an erosional material deposited upon the beveled edges of the Simpson and Arbuckle formations.

ROBERT ROTH

DRAWER L
BARTLESVILLE, OKLAHOMA
January 12, 1930

DISCUSSION

SOME APPLICATIONS OF THE STRAIN ELLIPSOID

In his paper on "Some Applications of the Strain Ellipsoid" in the November *Bulletin*, Theodore A. Link has discussed a very interesting and very important subject which deserves a much wider application in structural geology. The strain ellipsoid developed by Leith is a great help in determining the type and direction of stresses causing certain deformations. Mr. Link is quite right in emphasizing, as Leith did, the fact that the strain ellipsoid is three-dimensional and that its relation to geological problems must be visualized in three dimensions.

It is true that the strain ellipsoid is a conventional form and it is extremely difficult to produce one by deforming a sphere in the laboratory. It is difficult to produce either a perfectly homogeneous sphere or a homogeneous stress. However, the strain ellipsoid represents the operation of mathematical laws, and the characteristic shear planes may be produced in the laboratory and observed in the field. The strain ellipsoid, if correctly applied in the field, may be used to prove stress and strain relationships in the rocks of the earth's crust. As suggested by Mr. Link, great care must be exercised to distinguish shear joints from those due to other causes, inasmuch as the strain ellipsoid, incorrectly applied, proves nothing. The criteria for classification of joints have been discussed by Leith.[1]

As it is extremely improbable that we shall find examples of equal horizontal and vertical relief, the occurrences of oblate and prolate spheroids are probably unimportant to the structural geologist. The important thing is the strain ellipsoid relationship of two intersecting sets of parallel planes of shear. If the direction of greatest relief is horizontal, the shear planes will be vertical, their horizontal traces will intersect, and the lines of intersection of the planes will be vertical. If the direction of greatest relief is vertical, the shear planes will be inclined, their horizontal traces will be parallel, and the lines of intersection of the planes will be horizontal. After shear planes are formed, their attitude may be modified by subsequent folding of the jointed rocks, and the problem may be complicated by joints of several periods of deformation.

Inductive reasoning may suggest lines of research, and laboratory experiment may aid us in the interpretation of observed phenomena, but in geology, field data are most important. We should approach our field problems with open minds, gather our data in the field, and then seek what help we may in interpreting these data. To solve structural problems the strain ellipsoid should be applied to shear planes observed in the field. This application will show the direction of stress and the direction of greatest relief. It is incorrect to place the axes of the strain ellipsoid parallel with supposed directions of

[1] C. K. Leith, *Structural Geology*, revised edition (Henry Holt and Company, New York, 1923), pp. 47-58.

stress and greatest relief as suggested by Mr. Link. It is unsafe even to draw conclusions regarding structural geology by applying the strain ellipsoid to laboratory models, because these may not duplicate the field conditions.

It should be remembered that the mechanical properties of a sheet differ materially from those of a cube, although a sheet is an aggregate of cubes. In studying the deformation of the earth's crust, we should consider the mechanics of spheroidal shells. It is difficult to visualize in nature the plunger or vise so often used in experiments. The great sheets or spheroidal shells of sediments seem to be deformed largely by stresses transmitted through the basement rocks. For this reason the writer favors Mead's[1] system of experimental deformation of coatings on rubber sheets.

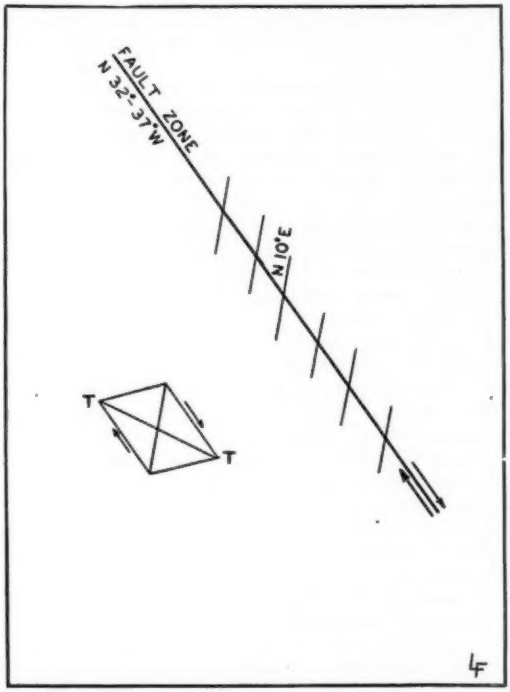

FIG. 1.—Sketch showing zone of tension fractures along San Andreas fault (after Omori). Strain diagram shows relation of axis of tension to the rotational stress arising from the movement.

[1]Warren J. Mead, "Notes on the Mechanics of Geologic Structures," *Jour. Geol.* Vol. 28 (1920).

It is questionable whether Mr. Link is justified in assuming that the greatest relief must be upward, even in mountain building. The amount of uplift is small compared with the amount of crustal shortening in the great mountain folds and thrust faults. Mr. Link has considered only simple compression. The greatest relief may be horizontal even at the surface in rotational stresses. This is shown by the surface movement along the San Andreas fault which caused the San Francisco earthquake in 1906. There the vertical movement ranged from 1 foot to 2 feet and the horizontal movement from 6 to 20 feet.

Mr. Link interprets correctly the writer's application of the strain ellipsoid to the structure of north-central Oklahoma. The regional, shear joint planes in this region are vertical; therefore, the planes of shear of the strain ellipsoid must be placed in a vertical position. This places the intermediate axis in a vertical position and the long axis must, therefore, be horizontal, indicating lateral relief. This does not necessarily imply deformation at great depth, as suggested by Mr. Link, but rather indicates deformation by rotational stresses. Mr. Link's argument that such deformation could only take place at considerable depth is disproved by the surface deformation incidental to the movement along the San Andreas fault in 1906. Omori[1] and many others have described zones of *en échelon* tension fissures occurring at the surface along the fault zone as shown in Figure 1. These tension fractures have exactly the same relation to the fault zone as the zones of *en échelon* faults of Oklahoma have to the movement along deep shear zones postulated by Fath[2] and Wood. The *en échelon* faults are not considered manifestations of planes of no distortion but are manifestations of the tensional stress incidental to shearing movement.

LYNDON L. FOLEY

TULSA, OKLAHOMA
November 26, 1929

AUTHOR'S REPLY

Field data are indeed most important in geology and the gathering of such data has occupied most of my time for the last ten years. To date I have never found a single solution of a structural problem with the aid of the strain ellipsoid conception.

We all have different tastes, likes, and dislikes. I have never regarded experimental deformation of coatings on rubber sheets as approaching conditions like those found in nature. (I may be wrong.)

As long as an overthrust fault is inclined, any movement along it must be resolved into two components, upward and tangential. It is the upward movement along such a fault, and the upward bending of strata which afford the

[1] F. Omori, "Preliminary Note on the Cause of the California Earthquake of 1906," *Bull. Imperial Earthquake Investigation Committee of Japan.*

[2] A. E. Fath, "The Origin of the Faults, Anticlines and Buried Granite Ridge of the Northern Part of the Mid-Continent Oil and Gas Field," *U. S. Geol. Survey Prof. Paper 128-C* (1920), p. 77.

greatest relief of stresses. In *rotational* deformation in the horizontal plane it is obvious that the relief must be primarily in the horizontal direction, but that phase was not discussed in my paper. I doubt very much if we can draw upon the San Andreas fault for comparison with the folds and tension faults of central Oklahoma, because the deep shear zones of Oklahoma are "postulated" and have not been demonstrated to the satisfaction of all geologists concerned. If they do exist, and if the joint planes described by Foley actually are shear planes, then Foley's application of the strain ellipsoid seems reasonable. However, I still believe that the structural conditions could be portrayed equally well without recourse to the strain ellipsoid.

THEODORE A. LINK

CALGARY, CANADA
January 3, 1930

SOME APPLICATIONS OF THE STRAIN ELLIPSOID

I have read with interest and concern the recent paper by Dr. Theodore A. Link[1] on "Some Applications of the Strain Ellipsoid." My long association with Van Hise and Leith, and with the structural problems of the pre-Cambrian of the Lake Superior region and of other highly deformed regions, has naturally developed a real fondness for the much used but frequently misunderstood strain ellipsoid. A wider understanding of its usefulness and limitations should be welcomed, and I heartily agree with the emphasis which Dr. Link has placed on the necessity of always visualizing and treating an ellipsoid of strain in its true three-dimensional aspect.

The strain ellipsoid is a purely imaginary three-dimensional figure borrowed long ago from the science of mechanics by students of structural geology. In simplest terms it is an imaginary conception of the form assumed by an imaginary spherical mass within a solid body as a consequence of deformation. Properly employed it is an almost indispensable aid in the analysis of the mechanics of rock deformation, and is useful in the exposition of facts and theories pertaining to many problems of rock deformation. Perhaps its greatest usefulness is in connection with actual field observations of deformed rocks as an aid to correct analysis of structural features observed. I am making no attempt here at an exposition of the strain ellipsoid and its applications. I am concerned only with the fact that the paper under discussion contains errors of fact and analysis which may be dangerously misleading to readers unfamiliar with the theory of the strain ellipsoid.

The second paragraph of the article follows.

> The relationship of the hypothetical planes of no distortion or planes of shear, with respect to the three mutually perpendicular axes of any given strain ellipsoid is absolutely definite (Fig. 1). The two planes of no distortion intersect each other along a line which includes the intermediate axis (*B-B*), and these planes of no distortion represent circular sections through the ellipsoid whose diameters equal the *length of the intermediate axis* (*B-B*). This must always be the case if there are three unequal axes. In this discussion the longest axis will be referred to as the *A-A* axis, the intermediate the *B-B*, and the shortest the *C-C* axis (Fig. 1).

[1] *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13 (1929), p. 1449.

The second sentence here quoted implies that there are two and only two "planes of no distortion" in the ellipsoid described. Obviously the planes described are the directions or orientations of the circular sections of the ellipsoid, *of which there are an indefinite number.* I have before me a sphere built up of circular discs of celluloid supported on an axial rod and held together by springs at each end of the rod. This sphere becomes an ellipsoid when it is deformed by tilting the discs relative to the rod simultaneously. Each disc is truly a *plane of no distortion.* The author's statement, that "......these planes of no distortion represent circular sections through the ellipsoid whose diameters equal the *length of the intermediate axis,*" is not a correct definition of planes of no distortion. The statement is true *only* when there is no strain in the direction of the intermediate axis.

The following paragraph follows the one already quoted.

> A *prolate spheroid,* in which the *A-A* and *B-B* axes are equal in length, has only one plane of no distortion which includes within it these two longer equal axes. Likewise, an *oblate spheroid,* in which the *B-B* and *C-C* axes are equal, can have only one plane of no distortion which includes within it the two shorter equal axes.

The terms "prolate" and "oblate" have been reversed throughout the paper, but in addition to this error there is the misconception that maximum circular sections of strain ellipsoids are necessarily planes of no distortion. Here, and throughout the paper, the author fails to see the utter inconsistency of calling circular sections containing axes of greatest shortening and axes of greatest extension, respectively, "planes of *no* distortion." All sections of ellipsoids of revolution (oblate and prolate spheroids) perpendicular to axes of revolution are circular, but *none of them is a plane of no distortion.* In the oblate spheroid *they are all greater* than the corresponding sections of the original sphere, and in the prolate ellipsoid they are all smaller.

I quote the next paragraph.

> A condition in which the *A-A* and *B-B* axes are equal (a *prolate spheroid*) could arise from compressive forces parallel with the *C-C* axis with an equal relief of stresses along the two equal axes, *A-A* and *B-B.* Expressed in another way, it would amount to a lateral elongation or relief equal to the upward relief of stresses. In this case, the one plane of no distortion or shear lies perpendicular to the *C-C* axis, if non-rotational compression caused the deformation.

In the first sentence an *oblate* spheroid is described. The second sentence conveys no meaning to me. In the last sentence is an error that naturally follows the misunderstanding of "planes of no distortion." Also in the last phrase of the sentence there is an erroneous assumption that the manner of application of stress has anything to do with the properties of a given strain ellipsoid. In the deformation described—non-rotational compression with equal lateral relief in all directions normal to the pressure—the plane of shear *does not* lie perpendicular to the *C-C* axis. This can not be a plane of no distortion as it contains the two axes of maximum elongation. In the example described there *is no plane of no distortion,* and no shear *plane.* There are in this case *lines of no distortion,* the unchanged diameters of the original sphere, all of which pass through the point of intersection of the axes, and together form surfaces which are the surfaces of two cones apex to apex. These cones of shear are familiar to all engineers who have tested cylinders of rock or concrete. They are nicely (but unknowingly) illustrated in "*b*" of Figure 3 of the paper discussed.

Before the later part of the paper is considered, attention should be called to a misconception expressed in the first footnote.

It is obvious that in considering a given sphere deformed into an imaginary ellipsoid, the two must be of equal volume; consequently, the problem becomes quantitative.

This is contrary to fact. The writer seemingly has not heard of "Poisson's ratio," familiar to students of mechanics. There is a change in density and consequently in volume with strain. (Rigorously, it may be said that there can be no planes of no distortion except in the case involving no volume change.) For most rocks the ellipsoid actually departs from a sphere by only a *very* small amount.

The discussion of "Regional Applications" contains no essential points of disagreement.

In the next section of the paper the author emphasizes the fact that the strain ellipsoid is "an imaginary conventional form." The excellent statement of Leith, "Any imaginable sphere of a solid body, when deformed in a single homogeneous strain, becomes a strain ellipsoid," is quoted, but the essential element of *single homogeneous strain* is neglected in later discussion of experimental evidence and in the attempt to cause a strain ellipsoid to "appear" by deforming a sphere of plaster of Paris. Naïve confession of disillusionment, or perhaps an attempt to be facetious, may be inferred in the statement, "The writer knows of no example of a hand specimen of a strain ellipsoid found or observed in the bed rock of the earth, nor an example of one produced in the laboratory."

I quote the first paragraph of the section on "Experimental Evidence."

Whether or not it would be possible to deform a perfect sphere of homogeneous material by compression into a true strain ellipsoid with the planes of no distortion and the three axes in their proper place remains to be demonstrated. Theoretically it should be possible. The writer deformed spheres of plaster of Paris by compression between two push-blocks, as illustrated in Figure 3, but no true strain ellipsoid resulted, nor did the planes of shear develop so that the direction of greatest compressional stress bisected the obtuse angles of the shear planes. These results, as well as practically all experiments in which cubes of homogeneous materials are subjected to compression, seem at variance with the current conception of the strain ellipsoid.

The attempt to change the plaster sphere into a strain ellipsoid by deforming it in the manner described failed because the entire sphere was not "in a single homogeneous strain." The points of contact flattened slightly, and the central cylindrical element of the sphere between the flattened ends failed by shear *on conical surfaces*. The strain ellipsoid representing the deformation of the inner mass of the sphere was an oblate spheroid—it could not be seen, *but it was there*, as were a multitude of others, one for each imaginary spherical unit of the mass which was small enough to have suffered *homogeneous strain*. The last sentence of the foregoing quotation reflects an utter misconception of the real nature of the ellipsoid of strain. Every imaginary sphere in every "cube of homogeneous material subjected to compression" becomes an ellipsoid of strain if it is small enough to suffer homogeneous strain, but of course these strain ellipsoids can not be seen or shelled out like peas from a pod.

In the final section the author discusses "Position of Planes of No Distortion, and Nature of Materials." This section begins with the same misconception that appears in various other parts of the paper.

> At the beginning of this article it was stated that if the *C-C* and *B-B* axes are equal (an oblate spheroid) there can be only one plane of no distortion including within it these two axes of equal compression. Furthermore, if the *A-A* and *B-B* axes are equal (a *prolate spheroid*) there is also only one plane of no distortion which includes the two axes of equal elongation.

Again the terms "oblate" and "prolate" are interchanged. Based on these two false premises is an analysis of the question of factors determining the relation of shear planes to the axes of strain ellipsoids.

> It is obvious that if the intermediate *B-B* axis is only slightly longer than the *C-C* axis of compression, but considerably shorter than the *A-A* axis of greatest elongation, the planes of no distortion should lie so that the *C-C* axis will bisect a small *acute* angle made by these planes, as shown in Figure 9.

I must confess that I have had difficulty in understanding this argument. Here again the author fails to see the inconsistency of calling sections containing axes of maximum strain "planes of *no* distortion." If in this quotation the term "circular sections" be substituted for "planes of no distortion," the statement becomes true, but of no importance as having any bearing on the manner of failure. The author has made the mistake of *neglecting to consider the original sphere* in relation to the ellipsoid of strain. Obviously it is correct to infer from his statement that both the *B-B* and *C-C* axes *are shorter than the diameter of the original sphere.* This pictures a strain produced by nearly equal compression from all directions normal to the *A-A* axis, or by an extensional stress elongating the *A-A* axis. It is essentially the ellipsoid of strain produced in a ductile wire under tension. A cone of shear would be formed. (Stretch a copper wire to rupture and examine the ends.) The planes of shear described do not exist.

> Likewise, if the intermediate *B-B* axis is only slightly shorter than the *A-A* axis of greatest elongation, but considerably longer than the *C-C* axis of compression, the planes of no distortion should lie so that the *C-C* axis bisects a large *obtuse* angle made by the planes of no distortion, as shown in Figure 9.

Here again the original sphere is neglected. Again we may substitute the term "circular sections" for "planes of no distortion" and the statement becomes perfectly true, but of no significance. The *B-B* axis must in this case be *longer* than the diameter of the original sphere. There seems to be little point in further analyzing an argument that begins with so unsound a foundation.

The conclusion, in the author's italics, is

> *The angle of intersection of the planes of no distortion is dependent upon the relative lengths of the three axes.* Consequently, it should be possible to produce, by simple non-rotational compression, an imaginary ellipsoid in which the axis of compression bisects either an acute or an obtuse angle of the intersecting planes of no distortion.

The italicized sentence clearly is based on several misconceptions and applies only to the strain ellipsoids in which the intermediate axis is equal to the diameter of the original sphere, and even in this limited application it is of no sig-

nificance in determining the angle of shear relative to direction of causal stress. The ellipsoid referred to in the second sentence must not only be imaginary but versatile.

This section of the paper is concluded as follows.

> The foregoing analysis points decidedly toward a harmonious agreement between Hartmann's Law and a correct conception of the strain ellipsoid. It shows that an imaginary strain ellipsoid can be produced by non-rotational compression in which the *C-C* axis of compression may bisect an angle as low as 1° or as high as 180°. Furthermore, it raises serious question regarding the current conception that when the axis of compression bisects a high obtuse angle the stresses which caused the strain were rotational. Regarding this problem the writer hopes to give additional discussions in a later article.

I am not aware of any lack of harmonious agreement between a *correct* conception of the ellipsoid of strain and "Hartmann's Law." I interpolate that in the second sentence the author refers to the angle between the planes of shear, and, if he does, the statement is ridiculous. I shall await with interest the "later article."

The paper is closed with five paragraphs of "Conclusions." The first paragraph is a reminder to students that the strain ellipsoid is a three-dimensional concept and an attempt to define its application. The second properly warns against the use of the strain ellipse without regard to the third dimension.

> The angle at which the planes of no distortion will develop in a given mass is dependent upon the nature of the material and the relative amount of relief along the axes of elongation.

This should include the factor of rate of deformation.

The third sentence in the third paragraph is unfortunately ambiguous.

> Brittle and rigid material will develop relatively low planes of shear *with very slight compressive forces* and will keep on developing them with the same definite angle relationship after prolonged application.

The italics are mine. Certainly the compressive stress required to cause failure of a "brittle and rigid material" depends on the *strength* of the material and the *manner in which it is confined*. If it is very weak it will fracture with "very slight compressive force," but what if it does? The significance of "prolonged application" I have tried in vain to understand. Perhaps the author had in mind *amount of compression*, but even this guess does not help me, as the amount of compression a "brittle" material may suffer before failure is extremely slight. He makes the following statement.

> Plastic material will not shear until prolonged application of compression, but after shearing has once commenced it will also be with the same definite angle relationship peculiar to the material in question, as demonstrated by Hartmann and so well understood in engineering practice. In rigid material the axis of compression normally bisects an acute angle of the planes of shear, while in plastic material an obtuse angle is bisected by the axis of compression.

Here, with vague, undefined terminology and turbid sentence construction, the author attempts to settle a highly complex and difficult question in the mechanics of the manner of failure of materials, on which the ablest students of mechanics have not agreed. What is "plastic material?" What is meant

by "prolonged application of compression?" Surely the *rate* of deformation is a governing factor, but it is not mentioned.

> Intersecting shear planes in the *horizontal* suggest *deep-seated compressive* forces, and intersecting shear planes in *cross section* indicate *surficial tangential compression.*

With this statement I can not agree. Intersecting shear planes in the horizontal indicate easier horizontal than upward relief from stresses, which situation may be due to several factors including rotational deformation of the region. Intersecting shear planes in cross section indicate easier upward relief than lateral, a condition that may exist at depth as well as at the surface.

> Finally, the application of the strain ellipsoid is to be regarded only as a convenient means whereby a given structural condition is made understandable.

Would that it were! Truly, "Its application *proves* nothing, but merely indicates a structural *interpretation*."

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DEPARTMENT OF GEOLOGY
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December, 1929

AUTHOR'S REPLY

Professor C. K. Leith's textbook *Structural Geology* is, I presume, generally regarded as the source book for the strain ellipsoid conception; therefore, it is proper to quote the definitions from that source. The relationship of the three principal axes and the planes of no distortion is, according to Leith,[2] as follows.

> In a strain ellipsoid with three unequal principal axes there are only two cross-sections which are circular in outline.... These planes, which are called *planes of no distortion* because they preserve a circular cross-section similar to a section of the original sphere, are also the planes of maximum shear.

There is essentially no difference between the statement criticised by Professor Mead in the second paragraph of my article and the one just cited. Inasmuch as I stated that "The two planes of no distortion intersect each other along a line which includes the intermediate axis (*B-B*)," it is obvious that the circular *cross sections* were in mind even though I referred to them merely as "circular sections." In view of this, Professor Leith must bear, with me, the criticisms of Professor Mead. It is in place to call attention to Leith's statement, "They preserve a circular cross-section *similar* to a section of the original sphere" (italics mine), and are not necessarily equal.

However, I am willing to accept either Professor Mead's or Professor Leith's version because the planes of all other circular sections of a specified ellipsoid lie parallel with the planes of the two large circular *cross sections;* consequently, the line of intersection of any other smaller pair of circular sections lies parallel with the intermediate (*B-B*) axis. The "sphere built of

[1]Introduced by F. H. Lahee.

[2]C. K. Leith, *Structural Geology* (Henry Holt and Company, New York, 1923), revised edition, pp. 23-24.

circular discs" which is deformed into an ellipsoid by tilting illustrates this idea very well. Likewise, the angle-relationship between the various smaller circular sections and the principal axes of a specified ellipsoid is exactly the same as that between the circular *cross sections* and the three axes.

The awkward reversal of the terms "prolate" and "oblate" spheroids is admitted with apologies to my readers and thanks to Professor Mead for calling attention to it.

In regard to the oblate and prolate spheroids, Professor Mead makes the objection that the circular cross section is the plane of no distortion because in the oblate it is larger and in the prolate smaller than the diameter of the original imaginary sphere. Again I refer to Leith, who says, in writing about the ellipsoid, "They preserve a circular cross-section *similar* to a section of the original sphere" (italics mine). Spheroids are described in many textbooks on mathematics as special cases of ellipsoids. However, Professor Mead states that in this connection we are not dealing with "planes" of no distortion, but merely with "*lines of no distortion*," which equal in length "the unchanged diameters of the original sphere, all of which pass through the point of intersection of the axes, and together form surfaces which are the surfaces of two cones apex to apex. These cones of shear are familiar to all engineers who have tested cylinders of rock or concrete. They are nicely (but unknowingly) illustrated in '*b*' of Figure 3 of the paper discussed." The foregoing discussion is not entirely acceptable to me. Why should we, in considering spheroids (which are related to ellipsoids) change from "*planes*" to "*lines?*" If this is permissible, there is the possibility that in considering the ellipsoid we are also dealing with *elliptical* cones of shear and lines of no distortion rather than "*planes*." All experimental evidence seems to point in that direction, and possibly the whole idea of "*planes*" of no distortion is incorrect. My version of the significance of the cones of shear was discussed at length in a previous contribution[1] and it seems appropriate to give a little more detail regarding what actually took place when the plaster of Paris spheres were deformed. The cones of shear, illustrated in the figure referred to by Professor Mead, are not merely two cones which meet apex to apex, but are an infinite number of "cones in cones." In the figure referred to in my paper we see only the two larger *outside* cones. Only after a sufficient amount of compression do they meet apex to apex, and before that stage is reached the lines, referred to by Professor Mead, do *not* pass through the point of intersection of the axes, nor is their length equal to that of the unchanged diameter of the original sphere. This is illustrated in Figure 1 of this discussion. As already suggested, it seems in place to consider that in connection with an ellipsoid there may be developed lines of no distortion the aggregate of which would give rise to elliptical cones of shear analogous to the circular cones in the spheroids.

The objection to my footnote, regarding constant volume, is not conclusive, because Professor Mead cancels it by admitting that "(Rigorously, it may be said that there can be no planes of no distortion except in the case involving no volume change.)." Inasmuch as the strain ellipsoid conception, as applied to

[1]Theodore A. Link, "The Relationship between Over- and Underthrusting as Revealed by Experiments," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 12 (1928), pp. 826-35.

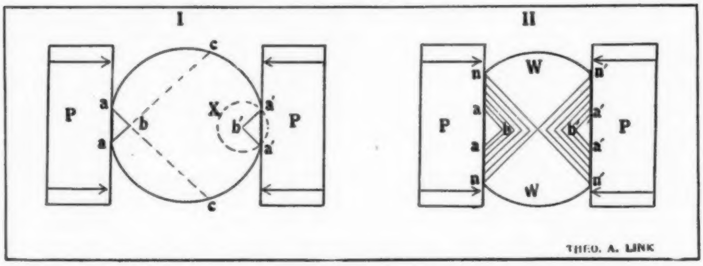

FIG. 1.—Illustrating the sequence of events during the compression of a sphere of plaster of Paris. The first manifestation (Stage I) is the development of small cones *a b a* and *a' b' a'* against the push-blocks "*P*." Notice that the lines *a b c* do not equal the diameter of the original sphere. Further compression causes the growth of successively larger cones until the final result is a series of "cones in cones," the outermost of which meet apex to apex so that the lines *n-n'* equal the diameter of the original sphere (Stage II). All the compression and change of volume is taken up within these cones while the material in the wedges (*W*) remains essentially unaltered. In an imaginary sphere "*X*" (Stage I) it is probable that the lines *a'b'* equal the radius of such a sphere.

structural geology, means very little or nothing without the planes of no distortion, anyone who uses it is doing so under the assumption of no volume change. Furthermore, it is far better to treat the matter "rigorously" than loosely. I actually believe that there *is* volume change and for that very reason the whole idea of the strain ellipsoid application to field problems in structural geology is not entirely sound. I have always felt this, and Professor Mead has now thoroughly convinced me of it. In connection with this same subject it is in place to call attention to the fact that Professor R. T. Chamberlin[1] calculated the depth of the Appalachian folds on the basis of an unchanged or constant volume, and others have followed suit.

My statement, "The writer knows of no example of a hand specimen of a strain ellipsoid found or observed in the laboratory," is termed by Professor Mead as, "naïve confession of disillusionment, or perhaps an attempt to be facetious." I reiterate the fact that a well known structural geologist, and several others, suggested to me that the "stretched pebbles" of Appalachian conglomerates might be considered as an example of hand specimens of strain ellipsoids. Hence, there actually *are* people who believe that ellipsoids may be "shelled out like peas from a pod."

Professor Mead has difficulty in understanding my various statements regarding the relative lengths of the three principal axes and the resulting position and the angle-relationship of the circular cross sections with respect to these axes. These statements are all based upon Leith's definition of the "planes of no distortion" already cited. Professor Mead maintains throughout that I do not "*consider the original sphere.*" In Figure 2 of this discussion I

[1] R. T. Chamberlin, "Appalachian Folds of Central Pennsylvania," *Jour. Geol.*, Vol. 18 (1910), pp. 228-51.

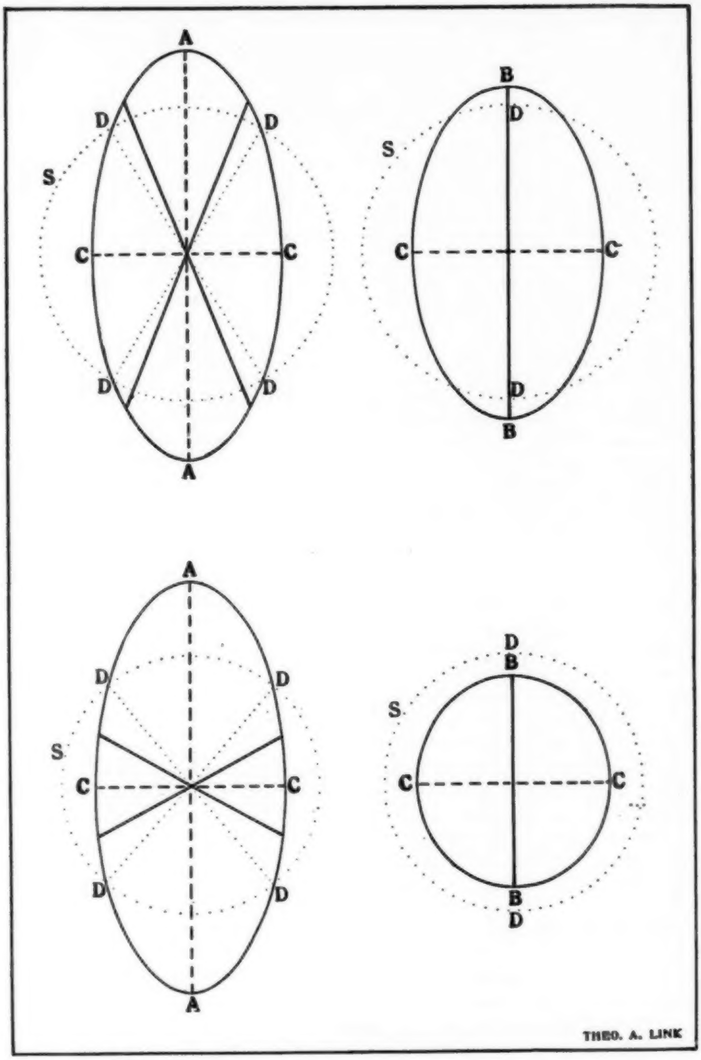

FIG. 2.—The original drawing of Figure 9 (see page 1463 of the paper under discussion) with the elements of the original spheres superimposed as dotted lines. (Essentially the same volume is postulated for the resulting ellipsoids.) In the upper diagrams the original sphere *S* was deformed so that an ellipsoid resulted in which the *B-B* axis was an axis of *intermediate elongation* (see upper right diagram). The cross sections through the intermediate axis, which equal the diameter (*D-D*) of the original sphere, are *elliptical* and intersect at a different angle from that of the *circular* cross sections (shown in heavy lines in upper left diagram). In the lower diagrams the original sphere *S* was deformed into an ellipsoid in which the *B-B* axis was an axis of *intermediate compression* (see lower right diagram). The cross sections through the intermediate axis, which equal the diameter (*D-D*) of the original sphere, are *elliptical* and intersect at a larger angle than the *circular* cross sections (lower left diagram). All other circular sections lie parallel with the circular cross sections; consequently, intersections of any pair will parallel the intermediate *B-B* axis. Obviously, if the *B-B* axis equals the diameter of the original sphere it is neither an axis of *elongation* nor an axis of *compression* and the problem may be regarded as two-dimensional.

have superimposed the *original* sphere on the original drawing of Figure 9 illustrated in the paper under discussion. He infers from the first of these statements "that both the *B-B* and *C-C* axes *are shorter than the diameter of the original sphere.*" This inference may be correct in one case, but in others it may not. It is dependent upon the direction and relative intensity of the compressive forces. In the lower part of Figure 2 both *C-C* and *B-B* are axes of compression. Is it not possible to have compressive forces acting upon a specified mass simultaneously parallel with the *C-C* and the *B-B* axis? By definition, is not the *B-B* axis termed "the axis of intermediate compression or elongation?" Compression parallel with the *C-C* axis may have a value of 10 while simultaneous compression, parallel with the *B-B* axis, may have a value of 8. If this is the fact, all the elongation will be parallel with the *A-A* axis and the resulting mass will be reduced along the *B-B* axis, also along the *C-C* axis. Similarly, elongation parallel with the *A-A* axis may have a value of 10, while simultaneous elongation parallel with the *B-B* axis may have a value of 8. In this situation all the compression is parallel with the *C-C* axis and the resulting mass will be extended along the *B-B* axis (see upper part of Figure 2). As a further example: if the original sphere has a diameter of 10 and we assume that the *C-C* axis, after compression, has a value of 6, the *B-B* axis a value of 10 (equal to the diameter of the original sphere), and the *A-A* axis has a value of 16.5+; under this condition we *must* assume that there has been *neither elongation nor compression* parallel with the intermediate *B-B* axis.[1] If this assumption *must* be made for all problems in structural geology, it is made under the limiting condition that all problems in structural geology are merely two-dimensional or cross-sectional, because then the intermediate axis does not stand for intermediate elongation or compression. There certainly are examples where there has been neither elongation nor compression parallel with the *B-B* axis, but such a situation appeals to me as an exception rather than the rule, and this special situation is illustrated by the wire-netting model of Leith's textbook and also by Professor Mead's "sphere built of circular discs."

Reading further in Professor Mead's discussion, I observe that he has criticized the following statement.

> *The angle of intersection of the planes of no distortion is dependent upon the relative lengths of the three axes.* Consequently, it should be possible to produce, by simple non-rotational compression, an imaginary ellipsoid in which the axis of compression bisects either an acute or an obtuse angle of the intersecting planes of no distortion.

The italicized sentence is decidedly *not* based upon the limited conception (previously discussed) that the length of the intermediate axis is equal to the diameter of the original sphere. Before going further, the reader is reminded that an inconsistency exists in Professor Mead's arguments. At this point he objects to what he erroneously interprets as a conception which limits the *B-B* axis to the diameter of the original imaginary sphere, while previously he objected to the idea that the *B-B* axis might be smaller than the diameter of the original sphere. If the reader will plot diagrams or construct models for himself he will be convinced that my conclusion is correct.

[1]It is assumed that there has been a slight volume change. With no volume change the *A-A* axis would have a value of 16.65+.

Regarding Hartmann's Law, I had reference to the statement by Dr. Stark[1] already quoted in the article under discussion, on page 1454.

The final attack on my conclusions is primarily a disagreement on the use of terms. The element "rate of deformation" is undoubtedly important, and the same applies to "strength of the material." I certainly am *not* ambitious enough to attempt a settlement (although I should like to) of "the highly complex and difficult question in the mechanics of the manner of failure of materials."

In the earlier part of his discussion Professor Mead saw "no essential points of disagreement" with my discussion of "Regional Applications," but when this is summarized in the conclusion of my paper he states, "With this statement I can not agree." In spite of this I am of the opinion that there may be some merit in my conclusion if an exception is made with reference to *rotational* deformation in the horizontal, a phase not intended to be discussed in my paper.

Professor Mead's closing statement may be interpreted in several ways and must, therefore, be left to the taste of the individual reader.

In conclusion, I wish to thank Professor Mead for the interest shown and the trouble he took in discussing my paper. It is imperfect at best; nevertheless, I believe that it contains points worthy of serious consideration. I should appreciate very much a discussion of non-rotational compression by Professor Mead, explaining his conception as to what the planes of no distortion are and where they lie in a specified ellipsoid. If his ideas are different from those given in Leith's textbook, why this prolonged silence?

THEODORE A. LINK

CALGARY, CANADA
January 3, 1930

[1] J. T. Stark, "The Primary Structure of the Kekequabic Granite," *Jour. Geol.*, Vol. 35 (1927), pp. 731-32.

REVIEWS AND NEW PUBLICATIONS

Die Gravimetrischen Verfahren der Angewandten Geophysik (The Gravimetric Method of Applied Geophysics). By HANS HAALCK. Mainka's Sammlung Geophysikalischer Schriften, Nr. 10. (Gebrüder Borntraeger, Berlin, 1929). 205 pp., 85 text figs., bibliography. Price, 16.80 marks ($4.00).

The contents of this book comprise: historical development of gravimetric measurements and the position of gravimetric methods among the geophysical methods of prospecting; properties of the potential and of level surfaces; measurement of the variation of the direction and intensity of gravity (chiefly a description of the pendulum method); measurement of the gradient and differential curvature with the torsion balance; the history, theory, and description of the Eötvös torsion balance; analyses of the result of torsion-balance surveys, the effect of topographic irregularities, graphical calculation of the terrane effects, construction of isograms, calculation of deflection of the vertical, anomalies produced by special types of subsurface bodies, diagrams as an aid to the interpretation of torsion-balance surveys, theoretical relation between gravimetric and magnetic measurements; physical-geological evaluation of observed gravity anomalies, general discussion, specific gravity of different types of rocks, practical examples, mine surveys, surveys of ore deposits, Kursk as an example of relation between gravity and magnetic anomalies; and field of applicability and future potentialities of the gravimetric method of exploration.

Although uninspired and rather elementary, this book gives a fairly well-balanced summary of the main points of the gravimetric method of prospecting. It is written in Haalck's usual easy German; the flow of thought is readily followed. The mathematical discussion is in terms of simple calculus. A more advanced exposition of the torsion-balance method and a more elementary statement of the mathematical theory of the torsion balance are available in English. The extensive series of English and American papers on the torsion balance, listed chiefly in the bibliography, seemingly had not become available to the author before the publication of this book. The book is essentially parallel with the gravimetric chapters of Ambronn and of Gutenberg.

Some statements do not agree with the reviewer's experience: for the study and analyses of faint anomalies, more exact methods of adjustment than that given by the author are necessary, and the least-square adjustment of a primary net of lines is less time-consuming and, on many surveys, less wearing on the disposition; in a few places, a simultaneous least-square adjustment of all stations gives a considerable increase in accuracy. Isograms ordinarily, rather than exceptionally, are of value in interpretation, except in simple situations. Maps showing equal value of U_{xy} and $U\Delta$ also are of value. Although superior to the analytical calculation, graphical calculation of the terrane correction, such as described by Haalck, is too slow, compared with

other methods, for routine work. The assumption of infinite extent at right angles to the vertical plane of the section is not permissible for many types of structures, but graphs similar to Haalck's charts (Figs. 70 *c* and *d*) but with prisms of finite length are as easily constructed and as easily used as the "infinite" charts. For structures without an axis of symmetry, different types of "contour" methods are available. The positive gravity anomaly characteristic of the Gulf Coast salt domes is not due solely to the fact that the specific gravity of the unconsolidated Plio-Pleistocene sediments is lower than that of the salt; it is present on shallow domes where no cap rock is present. The maximum number of stations possible per day per torsion balance is not three, but five. At least, this is true of Süss visual instruments, with not less than five readings, with favorable terrane, and with station intervals of one kilometer or less.

DONALD C. BARTON

HOUSTON, TEXAS
January 6, 1930

"Geology and Economic Deposits of the Moose River Basin." By W. S. DYER. *Thirty-seventh Annual Report of the Ontario Department of Mines, 1928*, Vol. 37, Pt. 6 (1929). 78 pp., 13 photographs, 2 maps, and 2 plates showing Devonian cephalopods.

The sedimentary basin under discussion covers the southwest shore line of Hudson Bay, extending 150 - 200 miles inland. The whole basin is enclosed by the pre-Cambrian rocks of the Canadian shield.

The stratigraphical column in the south part of this basin, on Moose River, includes Pleistocene deposits of glacial till, clay, and peat; Lower Cretaceous or Upper Jurassic (Matagami formation) clay, sand, and lignite up to 138 feet in thickness; Upper Devonian (Long Rapids and Williams Island formations) petroliferous black and gray shales and limestone up to 137 feet in thickness; Middle Devonian (Abitibi River formation) gray fossiliferous limestone up to 65 feet in thickness; Lower Devonian (Moose River formation) limestone and gypsum up to 50 feet in thickness; and Lower Devonian (Sextant formation) arkose and clays up to 50 feet in thickness, followed by pre-Cambrian. Farther north, Silurian and Ordovician are developed to a very considerable extent, possibly underlying the Devonian rocks in the Moose River basin.

Limestones of Onondaga age (Abitibi River) are good producing horizons in the Petrolia and Oil Springs fields of southern Ontario, but in the Moose River basin the thickness of sedimentary rocks is not sufficient to permit commercially important accumulation, even though favorable limestones and petroliferous shales are present. Small oil fields may possibly be located north and northeast of the Moose River basin, if the Ordovician and Silurian rocks are present under the Devonian, thus increasing the thickness of sediments very considerably. Favorable structural conditions can be easily mapped from the surface.

The conclusion of the paper indicates that though favorable stratigraphical and structural conditions are known to be present in the Moose River basin, the very important thin section of sedimentary deposits practically excludes

commercially important accumulations of petroleum. and at the very best only small wells will be brought in. Therefore, under present conditions of the crude oil market, the development of the area does not seem practical.

Other deposits of possible economic value in the Moose River basin include gypsum, lignite and peat, various clays, sands and gravels, limestone, and iron ore.

BASIL B. ZAVOICO

TULSA, OKLAHOMA
January 11, 1930

Geologic Map of Kentucky. Prepared by the *Kentucky Geological Survey*, Willard Rouse Jillson, state geologist (Frankfort, 1929). Colored map (scale 1:500,000), 2 geologic cross sections and 7 columnar sections, on sheet 31 inches by 61 inches. Price, postpaid, $2.00

Drawing on all available data up to October, 1929, Willard Rouse Jillson, state geologist and director of the Kentucky Geological Survey, has issued a new geologic map of Kentucky. The scale is 1 to 500,000, or approximately 8 miles to the inch. Sixteen color symbols are shown of the outcropping series from the lowest exposed Ordovician on the Cincinnati arch to the recent Quaternary alluvium. General economic and structural features are shown, including mines of coal, asphalt, and fluorspar; dikes, faults, folds; oil and gas fields, pipe lines, and power transmission lines.

The cartographic work is good and the coloring distinct and sharply defined, giving a pleasing appearance to the map.

Several columnar sections are shown, giving the formations in different parts of the state, and two long cross sections, one from Ohio River southeastward across the Pine Mountain fault, and the other an east-west section from Big Sandy River to the Mississippi.

One of the most interesting and valuable features of the new map is that it shows the serial divisions of the Mississippian and Pennsylvanian systems, which have never before been mapped. (These boundaries are founded on the work of such men as S. Weller and L. C. Glenn.) The Mississippian is shown in three colors, indicating the Osage, Meramac, and Chester; the Pennsylvanian is mapped to show the Pottsville, Allegheny, and Conemaugh.

The evolution of the geologic map of Kentucky dates from the original map made in the seventies under the direction of N. S. Shaler, which was followed by the one compiled by J. B. Hoeing, under C. J. Norwood, state geologist in 1904, and the one prepared by L. M. Sellier under Jillson's direction in 1917 and corrected up to 1923, and this map just off the press.

The new map shows a vast amount of cumulative detail and is a very creditable and timely contribution. It may be obtained from the Kentucky Geological Survey at Frankfort, Kentucky.

JAMES H. GARDNER

TULSA, OKLAHOMA
January 21, 1930

RECENT PUBLICATIONS

ALABAMA

"Magnetometer Study of Alabama Area," by L. Spraragen. *Oil and Gas Journal* (Tulsa, Oklahoma, January 2, 1930), pp. 37, 64-66, 4 maps.

CROOKED HOLES

"Straight Hole Drilling Practice in California," by John Franklin Dodge. *Oil Bulletin* (Los Angeles, California, January, 1930), pp. 30-31, 3 figs.

"Formulae for Acid Bottle Determinations in Crooked Hole Tests," by Alexander B. Morris. *Oil Weekly* (Houston, Texas, January 10, 1930), p. 30, 1 illus.

FRANCE

"Communication sur la recherche du pétrole dans la zone prépyrénéenne," by Pierre Viennot. *II^e Congrès International de Forage* (Paris, September, 1929), 22 pp., 9 figs.

GENERAL

"Die Erdölprovinzen der Vereinigten Staaten von Amerika und ihre tektonische Stellung," by Fritz Erdmann-Klingner. *Petrol. Zeits.* (Berlin, January 1, 1930), pp. 1-6, 1 map. A review and discussion of "Tectonic Classification of Oil Fields in the United States," by Walter A. Ver Wiebe. *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13 (1929), pp. 409-40, 1 fig.

"Sind Kalke als Muttergesteine des Erdöls zu werten?" by A. F. v. Stahl. *Petrol. Zeits.* (January 1, 1930), pp. 6-10.

"First Cross-Section of Regional Series Is Completed in Oklahoma," by William F. Lowe. *National Petroleum News* (Cleveland, Ohio, January 15, 1930), pp. 48-51, 53, 83, 1 geologic cross section. Describes progress of the A. A. P. G. research committee work through the subcommittee on Permo-Pennsylvanian stratigraphy.

GEOPHYSICS

"Essential Points in Use of Geophysics," by E. U. von Buelow. *Oil and Gas Journal* (January 2, 1930), pp. 34, 67-68, 104.

"The Earth's Magnetism." *U. S. Coast and Geodetic Survey Special Publication 117* (1925). Supt. Documents, Washington, D. C. Price, $0.15.

"Results of Magnetic Observations in 1928." *U. S. Coast and Geodetic Survey, Serial No. 455.* Supt. Documents, Washington, D. C. Price, $0.10.

GERMANY

"The Origin of the Petroleum of North Germany." *Petroleum Times* (London, January 4, 1930), pp. 5-6, 1 illus. Discussion of an article by H. Werner in *Zeits. für das Berg-Hütten und Salinewesen.*

KANSAS

"The Geology of Cowley County, Kansas," by N. W. Bass. *Kansas State Geol. Survey Bull. 12* (prepared in coöperation with the U. S. Geol. Survey). Price, $0.20.

OKLAHOMA

"Oil and Gas in Oklahoma. Kiowa and Washita Counties," by Roger W. Sawyer. *Oklahoma Geol. Survey Bull. 40-HH* (Norman, December, 1929), 15 pp., 1 map, 1 cross section.

PERSIA

"The Geology of Iraq." *Petroleum Times* (London, December 21, 1929), p. 1194.

"Sur la Géologie de l'Irak," by H. de Böckh and P. Viennot. *Comptes rendus des séances de l'Académie des Sciences* (Paris, December 2, 1929), t. 189, p. 1000.

TENNESSEE

"The Foraminifera of the Ripley Formation on Coon Creek, Tennessee," by Willard Berry and Louis Kelley. *Proc. U.S. Natl. Museum* (Washington, D. C., 1929), Vol. 76, Art. 19, pp. 1-20, pls. 1-3.

TEXAS

"Two New Mollusks of the Genera Ostrea and Exogyra from the Austin Chalk, Texas," by L. W. Stephenson. *Proc. U.S. Natl. Museum* (Washington, D. C., 1929), Vol. 76, Art. 18, pp. 1-6, pls. 1-3.

THE ASSOCIATION ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following applicants for membership in the Association. This does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these applicants, please send it promptly to J. P. D. Hull, Business Manager, Box 1852, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each applicant.)

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Sidney Powers, Dollie Radler, W. C. Spooner
Roy P. Lehman, Ellis, Kan.
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Richard E. Sherrill, Pittsburgh, Pa.
Roswell H. Johnson, R. E. Somers, I. Tolmachoff

NEW ORLEANS TECHNICAL PROGRAM, MARCH 20-22, 1930

Following is a supplementary list of authors and papers scheduled for the New Orleans meeting of the American Association of Petroleum Geologists, March 20-22, 1930. Forty-eight other papers were listed in the January *Bulletin*, pages 114-16.

SUPPLEMENTARY LIST OF PAPERS

1. Mississippi Embayment and Gulf Coast District
- Hugh D. Miser, "Paleozoic Rocks Found in Wells in the Part of the Gulf Coastal Plain South of the Ouachita Mountains"
- Theodore A. Link, "Experiments Referring to Salt-Dome Structure"
- F. M. Van Tuyl, "A Contribution to the Salt-Dome Problem"
- C. R. Ames, "Brief Résumé of Present Activities and Some Difficulties Encountered in the Development of Southern Louisiana Salt Domes"
- Alva C. Ellisor, "Marine Oligocene of the Coastal Plain of Texas and Louisiana"

2. Geophysics
- C. A. Heiland, "Teaching of Geophysical Prospecting"
- C. A. Heiland, "Transmission of the Instant of Explosion in Seismic Prospecting"
- C. A. Heiland and John H. Wilson, "Geophysical Investigations in Colorado"

3. Foreign
- S. L. Mason, "Geology of Oil Prospects in the Republic of Turkey"

4. *Geothermal Studies*
   - John A. McCutchin, "Determination of Geothermal Gradients in Oklahoma"

5. *Miscellaneous Subjects*
   - Fred M. Bullard and Robert H. Cuyler, "Preliminary Report on the Geology of Montague County, Texas"
   - Roy H. Hall and Arthur Price, "Valley Center Oil Field, Sedgwick County, Kansas"
   - Harry Hotchkin, "Oil Conservation, the Geologist's Viewpoint"
   - J. Harlan Johnson, "An Unconformity in the Colorado Group in Eastern Colorado"
   - Roswell H. Johnson and Sylvester H. Rynearson, "Practical Determination of the Optimum Spacing of Oil Wells"
   - Roswell H. Johnson and F. G. Parris, "Relative Reliability of Structure Contour Maps Made from Comparative Elevations and from Dip Readings"
   - Theodore A. Link, "Expressions of Salients and Recesses of the Rocky Mountain Front in the Foothills Belt of Central and Southern Alberta"
   - E. H. Sellards, "Pre-Cretaceous Rocks of the Balcones Fault Zone of Texas"
   - Parker D. Trask, "Origin and Environment of Source Sediments"
   - W. A. Ver Wiebe, "Ancestral Rockies"

SAN ANTONIO SECTION ANNUAL MEETING

The annual technical meeting of the San Antonio Section of the A. A. P. G. will be held Saturday, March 1, 1930, at the Kincaid Hotel, Uvalde, Texas. The program includes ten papers on southwest Texas. Following the technical session, a field trip will be taken on Sunday, March 2. A cordial invitation is extended to everyone interested. The San Antonio Geological Society is the second of the two officially chartered technical sections of the A. A. P. G. It received its charter in April, 1929. It has a large and active membership, holding regular technical and social meetings. Charles H. Row, of the Sun Oil Company, is president, and Kenneth Dale Owen, of the Penn Oil Company, 2922 Broadway, San Antonio, Texas, is secretary-treasurer. For further information, write the secretary.

Memorial

MAURICE B. SCHMITTOU

Maurice B. Schmittou, member of the Association, was drowned in southern Brazil on November 12, 1929. Details are lacking, but it is understood that his death was occasioned by his endeavor to swim ashore after jumping from a canoe while attempting to run difficult rapids. After a protracted search his body was recovered and buried, in accordance with the Brazilian law, near the scene of the accident. Recent word indicates that under special permission the body will be sent to Schmittou's home as soon as possible.

Maurice was born in Porterville, California, on June 25, 1899. He graduated from Porterville High School in May, 1918, and entered the University of California in August, 1919. He graduated from that university with an A. B. degree in geology in May, 1923, and the following year took additional graduate work at the same institution, during which year he was also an instructor in geography. At the university he was a member of Alpha Chi Rho social fraternity, and his scholastic attainments and personality received recognition in 1922 by his election to Theta Tau professional fraternity. In 1924 he was elected an associate member of Sigma Xi.

In June, 1924, Maurice went to Tampico, Mexico, as geologist for the International Petroleum Company, with which company he remained until February, 1926, when he was transferred to the Transcontinental Petroleum Company of Mexico. Later he left Tampico and went to Buenos Aires.

Schmittou's marked professional ability was recognized by his associates, both within and without the organizations with which he was connected. His scholarship record at the university was well above the average and, as the writer knows from personal association, his energy and diligence in the enervating climate of the Tampico oil fields were exceptional.

Since 1927 Maurice was engaged in the most difficult of field work in the more unsettled parts of northern Argentina, southern Brazil, Bolivia, and Paraguay. Work of this type requires more than professional ability; it requires patience, stamina, ingenuity, and resourcefulness, all of which Maurice had in large measure.

The profession has lost not only a member who consistently did his work with thoroughness and credit to himself and who showed great promise of exceptional accomplishment, but it has also lost a valuable personality. Maurice was not demonstrative, in fact, was a little reserved in his manner; friendship did not usually develop with him at first meeting, but, as acquaintanceship continued, all with whom he came in contact realized his worth. Sincerity was his most striking characteristic; he possessed thoughtfulness and consideration for others, that were most evident when most needed. Friendship with him stood the most rigid test, that of daily and continuous association under

the trying physical conditions imposed by Latin-American jungles, far removed from any diverting interest.

Although he was a good student, essentially serious-minded with regard to his work, Maurice was far from strictly academic in his outlook on life. He was interested in the course of the world's events; he was interested in athletics, in his early years at California, where he was especially active in baseball; and, on suitable occasions, he was interested in recreations.

Having been very closely associated with Maurice for two years at the university and for three years in Mexico, the writer feels that he knew him exceptionally well. We wish to express to his mother, Mrs. G. J. Schmittou, of Berkeley, California, and to his other relatives in San Francisco and Porterville, our deepest and most sincere sympathy.

L. G. PUTNAM

LOS ANGELES, CALIFORNIA
January 3, 1930

R. R. BRANDENTHALER

Rudolph Richard Brandenthaler, petroleum engineer with the U. S. Bureau of Mines, was killed on December 14, 1929, by a gas explosion at the experimental station of the Bureau at Bartlesville, Oklahoma.

He and several assistants were experimenting with air-gas lift equipment which had been installed under his supervision for the purpose of making a study of the laws of flow of oil and gas from oil sands. While thus engaged, the explosion, of unknown origin, resulted, causing his death and that of one of his assistants, Meredith F. Miles.

Mr. Brandenthaler was born at Milwaukee, Wisconsin, but in early youth he accompanied his family to Seattle, Washington, where he received both his high school and college education.

He entered the University of Washington in October, 1912, but did not receive his B. S. degree in mining and geology until June, 1921, due to the interruption of the World War.

From 1908 until 1912 and during the summers of 1912, 1913, and 1914 he spent most of his time in Alaska, working in the gold mines and with geological parties.

During the World War he served overseas with the engineers. He was in several major engagements, including St. Mihiel, Argonne, and Meuse-Argonne. He was promoted to the rank of captain. He was wounded, gassed, and shell-shocked, as a result of which he spent many months in hospitals, but obtained his discharge before he had fully recovered.

Following his graduation from the University of Washington in June, 1921, he went to the Matanuska coal field with the Alaska Engineering Commission. In 1922 he became resident geologist for the Union Oil Company at Santa Fe Springs, California. In 1924 he went with the Midway Gas Company of California on a study of depletion and gas reserves.

In 1925 he joined the staff of the United States Bureau of Mines, with headquarters at Bartlesville, Oklahoma, and up to the time of his death had

completed several oil and gas reports and had supervised the work of the production department and gas section of the Bureau.

Mr. Brandenthaler, as an engineer, has contributed materially to the thought and literature of the petroleum industry. As a man, he will be remembered for his cheery disposition, his unselfish devotion to duty, and his sterling integrity.

H. C. George

Norman, Oklahoma
January 21, 1930

AT HOME AND ABROAD

Lew Suverkrop, consulting petroleum engineer, of Bakersfield, California, has invented an improved flow valve for oil wells.

Charles Schuchert, in the *American Journal of Science* for January, 1930, presents extracts in English, entitled "Cretaceous and Cenozoic Continental Connections according to von Huene," translated from von Huene's paper on Cretaceous dinosaurs of Argentina, "Los Saurisquios y Ornitisquios del Cretaceo Argentino," *Anales del Museo de La Plata*, Vol. 3 (1929).

The Oklahoma City Geological Society has elected officers for 1930 as follows: J. T. Richards, Gypsy Oil Company, president; R. M. Whiteside, Shell Petroleum Corporation, vice-president; R. D. Jones, Shell Petroleum Corporation, secretary-treasurer.

Richard L. Triplett, formerly with the Gypsy Oil Company of Tulsa, Oklahoma, has been transferred to California, where he is connected with the geological department of the Western Gulf Oil Company, 1221 Subway Terminal Building, Los Angeles, California.

Alva Christine Ellisor, research paleontologist for the Humble Oil and Refining Company, Houston, Texas, was elected a Fellow of the Geological Society of America at the annual meeting of the society, December 26-28, 1929, at Washington, D. C.

James A. Tong, formerly of the Venezuela Gulf Oil Company, Maracaibo, Venezuela, is now taking special work at Johns Hopkins University.

Perry R. Hanson is president of the newly organized Tri-State Exploration Company, 708 Brown Building, Wichita, Kansas, which will do contract core drilling and consulting geology. Mr. Hanson's resignation from the Amerada Petroleum Corporation at Tulsa, Oklahoma, became effective January 15, 1930.

W. C. Kneale, formerly resident geologist with The Texas Company in the Artesia district, New Mexico, has been transferred to the Fort Worth office, where he will serve as petroleum engineer for the North Central Texas district.

James C. Templeton, managing director of the International Geophysical Prospecting Company, Ltd., is engaged in a survey of the El Mene and Tocuyo districts of the properties of the North Venezuelan Petroleum Company, Ltd.

Frederick G. Clapp, consulting geologist, with offices in New York and Paris, has an illustrated article on "Tehran and the Elburz" in the January, 1930, number of *Geographical Review*.

ALFRED C. LANE, of Tufts College, Cambridge, Massachusetts, has been made a member of the staff of consultants of the Library of Congress.

T. WAYLAND VAUGHAN, director of the Scripps Institution of Oceanography at La Jolla, California, has been appointed to represent oceanography on the general subcommittee for geology of the Science Advisory Committee for the Chicago World's Fair of 1933.

JOHN L. CHURCH has recently been made manager of the land department of the Union Oil Company at Los Angeles, California.

ORVILLE E. RHINEHART is reported to have mapped the Barker dome and CHARLES T. LUPTON to have checked it and made the location of the Black Hills Petroleum Company's well, which is claimed to be the first commercial well in South Dakota. The location is in the NW. ¼, Sec. 34, T. 6 S., R. 2 E., 27 miles northwest of Hot Springs. The depth is 1,328 feet in 6½ feet of pay sand believed to be the base of the Minnelusa, or the top of the Madison formation. The oil is black and has a Baumé gravity of 38.5°. Present production is estimated to range from 25 to 50 barrels.

G. E. GREEN is chief geologist of the new San Angelo, Texas, office of the Vacuum Oil Company.

C. A. RUSSELL, vice-president in charge of West Texas operations, also in charge of Gulf Coast operations, of the Republic Production Company, is located in the general offices at Houston, Texas.

E. HARBORT, professor in the Technische Hochschule, Berlin-Charlottenburg, well known for his contributions to the geology of the German salt domes, died on December 14, 1929.

WARD B. BLODGETT, of Los Angeles, California, is production manager of the Chanslor Canfield-Midway Oil Company, petroleum subsidiary in California of the Santa Fe Railroad interests.

WALTER E. HOPPER has resigned from the Arkansas Natural Gas Corporation at Shreveport, Louisiana, to devote all of his time to the business of the Southern States Company, Inc., of which he is president. The Southern States Company, Inc., was organized two years ago by Mr. Hopper and H. C. OTIS and specializes in the tubing of high-pressure oil and gas wells against pressure. The general office of the company is at 922 Slattery Building, Shreveport, Louisiana.

H. B. THOMSON, who headed production engineering work in the Seminole district for the Indian Territory Illuminating Oil Company, is now on the production engineering staff of The Pure Oil Company, at Fort Worth, Texas.

M. M. KORNFELD is taking graduate work this year at Leland Stanford University, from which he received his A. B. degree in geology in 1927. Mr. Kornfeld is micro-paleontologist for the Shell Petroleum Corporation at Dallas and Houston.

NEIL McDOWELL and Miss MILLIE MORRISON were married at Baird, Texas, on Tuesday, December 24, 1929. They can be addressed in care of Gulf Production Company, Drawer C, Houston, Texas.

FRED M. BULLARD, of the University of Texas, gave an illustrated lecture on his trip with the U. S. Geological Survey party into Alaska, before the meeting of the San Antonio Section of the A. A. P. G., January 6, 1930. Other visitors in attendance were A. R. DENISON, ROBERT J. RIGGS, and LAWRENCE R. HAGY. The total attendance was 66.

R. B. RUTLEDGE, Skelly Oil Company: please accept our apologies. We have taken undue liberties in this department with your name and company connections. We hope we now state correctly that you have relinquished your duties as district geologist for the Skelly Oil Company in Kansas to assume duties as assistant chief geologist of the Skelly at Tulsa, Oklahoma.

PIERCE LARKIN, consulting geologist, of Tulsa, Oklahoma, has been working on the Edwards Plateau, Texas.

R. E. DICKERSON, chief geologist of the Venezuelan Atlantic Refining Company, Maracaibo, Venezuela, has been elected district representative of the A. A. P. G. for South America, for the term of 1930-31.

JOHN A. KAY, who has been in charge of land and geological work for the Continental Oil Company, with headquarters at Wichita Falls, Texas, has resigned. J. J. MAUCINI will now be in charge of this district.

E. E. BOYLAN, who has been connected with the Gulf Oil Corporation in South America for ten years, has resigned to accept the position of general manager of the Caracas Petroleum Corporation in Venezuela, with headquarters at Caracas.

M. J. MUNN is in charge of the Little Rock, Arkansas, offices of the Cosden Oil Company.

G. C. WOOLLEY, formerly connected with the Midwest Exploration Company at Abilene, Texas, is now employed by the Derby Oil Company, Wichita, Kansas.

A spring meeting and field trip of the Society of Economic Geologists will be held at Charlottesville, Virginia, April 24-26, 1930. The Department of Geology of the University of Virginia and the Virginia Geological Survey will be the hosts of the society at this meeting.

ROBERT V. ANDERSON, of Menlo Park, California, has left for an extended stay in Europe. His temporary address is in care of the American Consul, Algiers, Algeria.

E. V. WOOLSEY, formerly in charge of the geological division of the Atlantic Oil Producing Company in south Texas, resigned his position effective January 1, 1930. He is living in Luling where he will probably engage in oil investments.

Edson S. Bastin, of the University of Chicago, is vice-president and chairman of the section of geology and geography of the American Association for the Advancement of Science.

R. D. Reed has moved from Alhambra to 1110 Glendon Way, South Pasadena, California.

John G. Bartram, geologist of the Midwest Refining Company, Denver, Colorado, has an article in the *Oil and Gas Journal* of January 23, on "Possibilities in the Julesburg Basin (Wyoming and Colorado)." It is illustrated by structure contour maps.

Any graduate or former student of Indiana University attending the New Orleans meeting is urged to get in touch with Tom C. Hiestand, W. C. McBride, Inc., Exhibit Booth 11, the Venetian Room, Lobby floor of the Roosevelt Hotel, in order to arrange for a school luncheon.

DIRECTORY OF GEOLOGICAL SOCIETIES

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SECRETARY-TREASURER - - HARRY ROGATZ
PHILLIPS PETROLEUM COMPANY

MEETINGS: FIRST AND THIRD FRIDAY NOONS, EACH MONTH. PLACE: LONG HORN ROOM, AMARILLO HOTEL

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VICE-PRESIDENT - - WILLIAM J. NOLTE
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SECRETARY-TREASURER - - A. M. LLOYD
SUN OIL COMPANY

MEETINGS: SECOND FRIDAY, EACH MONTH, AT 6:30 P. M.
LUNCHEONS: FOURTH FRIDAY, EACH MONTH, AT 12:15 P.M.
PLACE: WICHITA CLUB, NATIONAL BUILDING

TULSA GEOLOGICAL SOCIETY

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SECRETARY-TREASURER - - E. A. MARKLEY
BARNSDALL OIL COMPANY

MEETINGS: FIRST AND THIRD MONDAYS, EACH MONTH, FROM OCTOBER TO MAY, INCLUSIVE, AT 8:00 P. M., FOURTH FLOOR, TULSA BUILDING. LUNCHEONS: EVERY THURSDAY, FOURTH FLOOR, TULSA BUILDING.

KANSAS GEOLOGICAL SOCIETY

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612 BROWN BUILDING

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GYPSY OIL COMPANY

SECRETARY-TREASURER - - PERRY R. HANSON
708 BROWN BUILDING

REGULAR MEETINGS, 12:30 P. M., AT INNES TEA ROOM, THE FIRST SATURDAY OF EACH MONTH. VISITING GEOLOGISTS ARE WELCOME.

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HALLIBURTON OIL WELL CEMENTING COMPANY
526 RICOU-BREWSTER BUILDING

MEETS THE FIRST FRIDAY OF EVERY MONTH, ROOM 605, SLATTERY BUILDING. LUNCHEON EVERY MONDAY NOON, WASHINGTON HOTEL.

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HOUSTON, TEXAS

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"Leaving the Lela bench mark on the Rock Island Railway, I carried the altimeters north about fifteen miles into the field, running elevations en route. After running most of the elevations in the field, I returned to Lela. About seven hours had elapsed between the first reading on the bench mark and the second reading on the bench mark. During this time intermittent showers occurred. The day was cold, raw, windy, and in addition we did not complete the traverse until darkness had set in. On checking back we found the variation in altimeter reading had been very constant during the successive hours of the work, and even more surprising found that Y level elevations run by another company the next week agreed closer with our altimeter elevations than they did with the average of our plane table elevations which had been secured by various companies over the same traverse.

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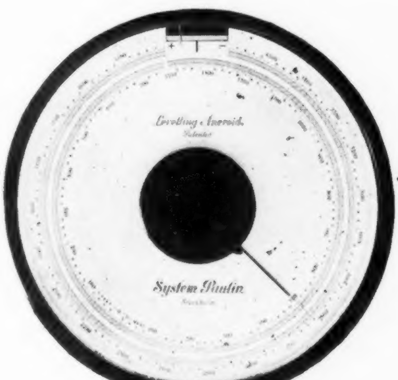

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